AN INVESTIGATION OF ROLLING-SLIDING CONTACT FATIGUE DAMAGE OF CARBURIZED GEAR STEELS

by

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ABSTRACT

The goal of this study was to evaluate the differences in RSCF performance between vacuum and gas carburized steels as well as to investigate the evolution of damage (wear and microstructure changes) leading to pitting. Vacuum and gas carburizing was performed on two gear steels (4120 and 4320) at 1010°C. The carburized specimens were tested in the as-carburized condition using a RSCF machine designed and built at the Colorado School of Mines. The tests were conducted at 3.2 GPa nominal Hertzian contact stress, based on pure rolling, 100°C, and using a negative twenty percent slide ratio. Tests were conducted to pitting failure for each condition for a comparison of the average fatigue lives. Pure rolling tests were also conducted, and were suspended at the same number of cycles as the average RSCF life for a comparison of fatigue damage developed by RCF and RSCF. Incremental tests were suspended at 1,000, 10,000, 100,000, and 200,000 cycles for the vacuum carburized steels to evaluate the wear and damage developed during the initial cycles of RSCF testing and to relate the wear and damage to pitting resistance. Incremental damage was not investigated for gas carburizing due to the limited number of available specimens.

The vacuum carburized samples showed a decreased pitting fatigue resistance over the gas carburized samples, possibly due to the presence of bainite in the vacuum carburized cases. Pitting was observed to initiate from surface micropitting and microcracking. A microstructural change induced by contact fatigue, butterflies, was shown to contribute to micropitting and microcracking. Incremental testing revealed that the formation of a microcrack preceded and was necessary for the formation of the butterfly features, and that the butterfly features developed between 10,000 and 100,000 cycles. The orientation and depth of butterfly formation was shown to be dependent upon the application of traction stresses from sliding. RSCF butterflies formed nearly parallel to the rolling direction at a large range of depths. RCF butterflies formed at about 45° to the rolling direction in a more narrow range of depths. The surface roughness and surface profile were observed to change quickly in the first several thousand cycles of RSCF testing leading to a reduction in contact stress and increase in lambda ratio (ratio of lubricant fluid film thickness to composite surface roughness). The ability of a carburized sample wear track to reach and maintain a steady state morphology (run-in condition) during testing is postulated to translate to increased RSCF resistance.
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CHAPTER 1: INTRODUCTION

One of the most common failure modes of components subject to sliding contact, such as gears or bearings, is pitting. Pitting is the direct result of cracking induced by rolling or combined rolling-sliding contact fatigue. Extensive work has been completed to understand the pitting resistance of steel under pure rolling conditions. However, a combination of rolling and sliding contact fatigue occurs during the mating of gear teeth as well as in some bearing systems. This additional sliding component is known to have an important effect on the pitting mechanism. As such, the ability to test gear/bearing steel under both rolling and sliding conditions was of interest in this work. One aspect of the project was the improvement of a rolling-sliding contact fatigue machine built previously at the Colorado School of Mines to allow for robust, reliable, and repeatable pitting evaluation with the ability to control the extent of sliding during testing.

One method known to improve the pitting resistance of gear steels is to surface harden by carburizing. Vacuum and gas carburizing was performed in this study on two common gear steel materials. Vacuum carburizing was performed to assess the effect of the absence of intergranular oxidation on rolling-sliding contact fatigue performance. Gas carburized samples were heat treated at a higher-than-typical temperature to match the vacuum carburizing temperature. Also, by increasing the carburizing temperature, the time for carburizing can be reduced and production rates can be increased. Consequently, it was of interest to understand the effect of the increased carburizing temperature on pitting resistance.

The carburized steel samples were subject to rolling-sliding contact fatigue testing until a pit formed. Material characterization was performed to assess the effects of the different carburizing treatments on pitting resistance, material properties, microstructure, carbon profiles, and residual stress. After testing, the samples were analyzed to investigate failure modes, microstructure changes, and wear. Additional tests were performed but suspended before the formation of a macropit to investigate the changes in testing conditions (surface roughness and wear) and to investigate the origin of microstructural alterations and microcracks.

Industrially, this research is relevant in two ways. First, heat treatments and material selection may be optimized based on understanding of pitting fatigue performance. Vacuum carburizing can increase cost, heat treating complexity, and is not always available; thus it is important to understand the potential benefits, or drawbacks, of vacuum carburizing compared to gas carburizing. Some gear materials are higher cost than others due to increased alloying additions such as nickel. This work has the potential to clarify the benefit of more expensive gear materials in terms of rolling-sliding contact fatigue.
behavior. Secondly, analysis of microstructural changes during rolling-sliding contact fatigue, especially before the formation of a macropit, can be used to understand failure initiation mechanisms and potentially the steel processing, alloy selection, and heat treatments necessary to improve gear material resistance to these failure modes.
CHAPTER 2: LITERATURE REVIEW

This chapter presents background information pertinent to the research conducted during this work. The principles behind carburizing are presented, as carburizing was the case hardening method selected for study. Contact fatigue principles are reviewed. The variables which affect the contact fatigue resistance of carburized gear steel are presented. Microstructure changes, failure mechanisms, and wear during contact fatigue are also discussed.

2.1 Carburizing

Carburizing is a heat treatment in which a component, typically fabricated from low carbon steel, is heated to a temperature sufficient to develop an austenitic microstructure, and held in a carbon rich atmosphere. Carbon diffuses into the austenite and the component is subsequently quenched and tempered to form a high hardness, wear resistant case with a core possessing relatively higher toughness. The carbon content is typically controlled to be between 0.8 and 1.0 weight percent to prevent complications associated with carbide formation, brittle martensite, and excessive retained austenite [1]. There are different methods of introducing carbon into steel. These include gas carburizing by surrounding the component in a carbon rich gaseous atmosphere, liquid carburizing by submerging the component in a carbon bearing salt bath, pack carburizing using solid carbonaceous compounds, or vacuum carburizing using carbon bearing gases at low pressures. For this study, gas and vacuum carburizing was investigated.

2.1.1 Vacuum Carburizing

Vacuum carburizing typically involves five steps. First is a heat and soak step at the carburizing temperature to allow the component to come to a homogenous temperature. This step should only be long enough to achieve a uniform temperature in the carburized component. Excessive soak times lead to austenite grain growth [2]. The second step is a boost step to introduce carbon to surface austenite. An important consideration for the boost stage in vacuum carburizing is the control of the carbon concentration of the surface of the steel component relative to the maximum solubility of carbon in the austenite at the given heat treating temperature [3]. If the carbon content of the surface exceeds the maximum solubility of austenite then carbides and a carbon deposit form. These features, particularly the carbides, can decrease the diffusion of fresh carbon into the austenite and retard the carburizing process [3]. The surface carbon content is related to both the carbon potential of the atmosphere and the boost time. The actual carbon potential of the atmosphere is difficult to control and model due to the numerous carbon-species decomposition chemical reactions occurring rapidly in the low pressure atmosphere. These reactions lead to a very high carbon potential [3, 4]. The high carbon potential is not readily controllable.
as a process variable in vacuum carburizing [2]. Therefore, the time allowed for the boost stage is a very important consideration in designing a vacuum carburizing heat treatment [3]. Third, a diffusion step is used to provide a gradual carbon diffusion profile between the case surface and the component core. In this step the furnace atmosphere is replaced by a non-carbon bearing gas such as nitrogen at the carburizing temperature and held, allowing the carbon to diffuse deeper into the austenitic component. Without the diffusion step the resulting abrupt change in hardness/carbon content between the case and core (illustrated schematically in Figure 2.1) would lead to undesirable case hardened properties [2]. The combination of the boost and diffuse steps is commonly referred to as a cycle. There are often multiple cycles employed during a vacuum carburizing treatment to attain the desired carbon profile and case depth, see Figure 2.1. The fourth step is quenching to produce a hard martensitic case. Quenching can be done by immersion in oil or by rapidly introducing cool gas such as nitrogen or helium. The use of controlled gas quenching has been shown to reduce the distortion of carburized component by providing a more uniform thermal gradient during quenching [6, 7]. The potential disadvantage of gas quenching is a relatively slower cooling rate as compared to oil immersion [7]. The reduced cooling rate may allow the formation of non-martensitic transformation products [8]. Finally, the carburized component is tempered to achieve an optimum combination of strength, toughness, and hardness [8].

![Figure 2.1](image.png)

Figure 2.1  Schematic illustrations of (a) the difference between boost and diffuse carbon profiles in vacuum carburizing and (b) the effect of number of boost and diffuse cycles on carbon profile during vacuum carburizing.

2.1.2  Gas Carburizing

Gas carburizing is the most common carburizing technique for large scale production due to the ability to accurately control process variables and the absence of special heat treating requirements [1]. In
gas carburizing carbon is introduced into the surface of the steel by various interactions between the carbon bearing atmosphere gasses and the solid solution austenite. One of the most important carburizing reactions is given by Equation (2.1) [9].

\[
\text{CO}_2(\text{g}) + \text{C} \rightarrow 2\text{CO}(\text{g})
\]  

(2.1)

where C is carbon introduced into the austenite. When the reaction defined by Equation (2.1 is in equilibrium, the ratio of CO$_2$ and CO maintains a given carbon potential. This carbon potential develops the surface carbon level in the austenite. If the partial pressure of CO in the carburizing atmosphere exceeds the partial pressure necessary to maintain equilibrium, the reaction will proceed to the left and the carburizing reaction occurs allowing the carbon content of the austenite to be increased to some desired level [1]. Figure 2.2 illustrates the point that the CO content of the carburizing atmosphere must be much higher than the CO$_2$ content for carburizing to occur. If on-the-other-hand the CO$_2$ partial pressure is raised above its equilibrium value the reaction will proceed to the right and decarburization will occur. This latter condition may be desirable if the initial carburizing creates a surface carbon content that is too high. The carbon content can then be lowered to the desired level. For gas carburizing this step is referred to as “diffusion”. Like in vacuum carburizing, the diffusion step in gas carburizing also allows the carbon at the surface to diffuse into the interior of the steel [1]. Quenching is typically performed using heated oil. Distortion is a relatively common occurrence in gas carburizing when quenching is not carefully controlled [8]. The extent of distortion can be minimized by stepping down the temperature of a component from the carburizing temperature prior to quenching [10], to reduce the thermal gradients.

![Equilibrium percentages of carbon monoxide and carbon dioxide required to maintain various carbon concentrations (in weight percent) at 975°C (1790°F) in plain carbon and low-alloy steels. Adapted from [11].](image)

Figure 2.2
2.1.3 Intergranular Oxidation during Carburizing

The atmosphere developed in a gas carburizing furnace is described as endothermic. The combustion of the fuel gas (methane, propane, or butane) with oxygen creates oxygen bearing gasses such as carbon dioxide, carbon monoxide, and water vapor [12]. The oxygen present in these gases may react with metal atoms in the steel components during carburizing, creating surface and subsurface oxides. The endothermic atmosphere develops a negative oxygen potential for iron and many of the primary alloying elements in steel alloys, thereby preventing oxidation of the bulk material. However, some alloying elements such as manganese, silicon, and chromium have a positive oxidation potential and readily form oxides as illustrated in Figure 2.3. Chromium tends to form dispersed oxides within the austenite grains at relatively shallow depths (up to 8 to 10 µm). Manganese and silicon develop intergranular oxidation (IGO) along austenite grain boundaries. The IGO typically penetrates deeper into the case, around 20 to 25 µm below the surface [1, 12]. A study examining alloying effects on IGO formation in gas carburizing showed that reducing manganese and silicon contents virtually eliminated the presence of IGO which in turn led to an increase in the bending fatigue strength of 4320 carburized steel [13].

![Oxidation Reactions chart](image)

IGO is thought to adversely affect the fatigue resistance of carburized case microstructures in two ways. First, the oxides are hard, brittle particles that act as stress concentrations and possible fatigue crack initiation sites [12]. Second, the material adjacent to oxides will have its transformation behavior modified [13, 14]. The formation of the oxides effectively robs the surrounding microstructure of alloying elements which impart hardenability to the steel. Non-martensitic transformation products such as pearlite
and bainite may be able to form at the surface upon rapid quenching. The formation of these microstructural components lowers the surface compressive residual stresses and increases susceptibility to fatigue crack initiation [17].

2.2 Hertzian Contact Stress Overview

Damage that occurs during contact fatigue results from the cyclic Hertzian contact stresses developed due to the contact between two bodies (bearings or gear teeth). The contact stresses lead to octahedral and orthogonal shear stresses in the subsurface of the material bodies. Figure 2.4 schematically illustrates how a cylinder rolling over a flat body in the absence of friction develops subsurface stresses. The stress created just below the contact is the maximum shear stress (octahedral). It occurs at 45° to the contact surface [18]. Orthogonal shear stresses which are oriented parallel and perpendicular to the contact surface are created in-front of and behind the point of contact. The leading orthogonal stress has the opposite sign of the trailing stress [18]. The magnitudes of the orthogonal stresses are always lower than the magnitude of the octahedral shear stress. However, the range of the orthogonal stresses is higher than the octahedral stress and is thought to be a more potent contributor to the development of contact fatigue damage [19].

Localized plastic deformation from the stress states developed during Hertzian contact can occur if the maximum shear stress exceeds a critical value defined by the Tresca (maximum shear stress) or Von Mises yield criteria [20]. The Tresca criterion only considers the maximum and minimum principal stresses while the Von Mises yield criterion also includes the intermediate principal stress. More information regarding the calculation of these stresses and the Hertzian contact pressure from which they develop can be found in the experimental procedure chapter.

2.3 Microstructural Changes During Contact Fatigue

Alterations in martensite/bainite microstructures have been observed as a result of contact fatigue in components such as gears and bearings as well as in samples from contact fatigue testing. There are three types of changes that have been observed using light optical microscopy (LOM) after etching and each is identified based on etching response. The first type of microstructure change is referred to as “dark etching areas” (DEA) which appear darker than the rest of the microstructure after etching with nital. The second type of microstructure alteration is called “white etching areas” (WEA) or “white etching bands” (WEB). WEA and WEB are not etched by nital/picral and appear white when viewed under LOM. The third change is related to WEA. Localized WEA structures form around non-metallic inclusions and are referred to as “butterflies”. The formation of DEA, WEA/WEB, and butterflies depends on the local magnitude of the applied shear stress from the Hertzian contact pressure and the number of applied stress cycles. Below certain critical stresses and numbers of stress cycles,
microstructure changes are not observed [21]. These critical stresses/cycles are not indicated clearly. It should be noted that through-hardened bearing steels under pure rolling conditions have been the primary focus of study in regard to microstructure changes.

2.3.1 Dark Etching Areas

DEA are typically seen after a few million contact stress cycles [19, 20]. DEA forms due to local plastic deformation of tempered martensite resulting from contact stresses locally exceeding the flow stress of the material at depths of maximum shear stress. The dark etching response of DEA is characteristic of high temperature tempered martensite [24]; however, temperatures of contact fatigue testing usually do not exceed 120 °C. It was postulated by G. Vasilica et al. [22] that modifications of local chemical compositions by carbon diffusion could be assisted by stress gradients. Because DEA is formed locally, not uniformly (as would be expected if DEA formation was temperature related [25]) at a depth corresponding to the maximum shear stress, there appears to be a stress dependence of DEA.

![Figure 2.4](image.png)
formation [20, 21, 23]. Other researchers have reported fine grained, heavily-dislocated, acicular structures within the DEA oriented at approximately 45° to the rolling direction [26] which were suggested to be precursors to the formation of WEA/WEB.

G. Vasilica et al. [22] showed that the amount or size of DEA correlates to the number of loading cycles, and strongly relates to the applied load/contact stress [22]. The authors conducted contact fatigue tests on lubricated, type 6208 ball bearings manufactured from RUL-1 steel (1.5% chrome 0.3% manganese). Hydraulically applied, radial loads varied the cyclic contact stresses from 3.12 to 5.56 GPa. The tests were suspended at given numbers of fatigue cycles to investigate the extent of DEA formation. Figure 2.5 shows the DEA observed after etching with 5 percent nital for four seconds along with the

![Micrographs of DEA formed in RUL-1 steel type 6208 bearing raceways](image)

Figures 2.5 Micrographs of DEA formed in RUL-1 steel type 6208 bearing raceways (a)-(d) tested at 80 and 120°C. (e) DEA microstructure at 500X. Etched with 5 percent nital for four seconds [22].
corresponding applied contact stress and number of cycles. The extent of DEA formation in the bearing raceways increased somewhat with the number of applied stress cycles (Figure 2.5a versus Figure 2.5d). The largest factor influencing the observed amount of DEA appeared to be the contact stress (Figure 2.5a versus Figure 2.5b). Figure 2.5e shows the fine tempered martensite structure containing temper carbides observed at 500X magnification in the DEA.

### 2.3.2 White Etching Areas

WEA WEB (Figure 2.6) form at the same depth in the contact material subsurface as DEA after a high number of cycles (on the order of $10^8$ to $10^{11}$ cycles depending on contact stress) [21]. Initially WEA forms at shallower angles of $20^\circ$ to $30^\circ$ to the contact surface. After further cycling, WEA develops at steeper angles, around $75^\circ$ to $85^\circ$, to the contact surface [27]. If the stress/rolling direction is reversed, the WEA orientation will reverse suggesting the stress dependence of their formation [28].

![Image of WEA structures](image)

**Figure 2.6** WEA structures formed during rolling contact fatigue (RCF) testing of 1% carbon, 0.5% manganese, and 1.5% chromium steel sample. Tested at 150°C and 5.4 GPa for $2 \times 10^8$ cycles. (a) Parallel to the wear track etched with nital. Rolling direction to the left. (b) Transverse to the wear track etched with picral. Rolling direction out of the page. Images taken from [29].

The structure of the WEA has been reported to consist of lenticular carbides between a fine-grained ferrite-like phase which is free of resolvable carbides [24]. Harada et al. [26] confirmed the observation of the fine grained ferrite structure using TEM. After extensive plastic deformation of the parent martensite a structure of fine dislocation cells develops within the ferrite-like phase. The
Dislocation density is similar to that of the parent martensite but the substructure resembles that seen in heavily strained ferrite [21]. The remarkable directionality of the WEA shown in Figure 2.6a is thought to be due to the stress dependence of WEA formation. However, an accepted mechanism explaining the observed directionality of the WEA has not been put forth. It has also been proposed that WEA form around hydrogen cracks although this mechanism has not been fully explained [30].

The mechanism of WEA formation is controversial and not well understood [21, 22]. It is believed that WEA formation is related to “mechanical tempering”. Theories in the literature suggest that dislocation motion due to localized plastic deformation enhances carbon diffusion. The carbon diffuses out of the martensite matrix (and from dissolving carbides) to the lenticular carbides leading to the white etching response. In support of the stress assisted carbon diffusion mechanism, Mitamura et al. [31] conducted a kinetic analysis of RCF failure of 52100 bearing samples at different RCF temperatures between 130°C and 170°C (226°F and 338°F). The summary of their results is given in Figure 2.7 which present Arrhenius plots used to calculate the activation energy of pitting failure. The “activation energy” of pitting failure, which was shown to correlate well to WEA formation, was determined to be 78 kJ mol\(^{-1}\) (independent of life definition, \(L_{10}\) versus \(L_{50}\), and stress, 4.6 versus 5.5 GPa), which corresponded well to the activation energy of carbon diffusion in ferrite (84 kJ mol\(^{-1}\)).

![Figure 2.7 Arrhenius plots of 52100 bearing samples tested by Mitamura et al. [31] at contact stresses of (a) 4.6 GPa and (b) 5.5 GPa.](image)

### 2.3.3 Butterfly Structures

Butterfly structures are identified from the obvious butterfly-like appearance of the feature. An example of a butterfly formed in a 52100 RCF specimen is shown in Figure 2.8. The “body” of the butterfly is usually a hard, non-metallic inclusion such as alumina (\(\text{Al}_2\text{O}_3\)) and the “wings” reportedly
[31, 32] have the same structure as WEA. Like WEA, the formation of the wings has been associated with carbon diffusion and carbide dissolution. The dissolving carbides within butterfly wings are shown in Figure 2.9 [30]. Cracking is typically observed near the butterfly wings and usually originates at the inclusion. Al₂O₃ inclusions are the most common inclusion type around which butterflies form, although in rare cases, they have been seen around elongated manganese sulfide (MnS) inclusions [25]. It was proposed that failure occurs when the crack grows to a sufficient length to reach the contact surface leading to pitting [34].

There are differences between WEA and butterfly wings. Butterflies form much sooner than WEA, presumably due to the high stress concentration around inclusions [35]. Unlike WEA, it has been proposed by Schlicht et al. [34] that a prerequisite for butterfly white etching wing formation is a crack initiating at the inclusion/matrix interface. There is a stress concentration which develops around the non-metallic inclusion due to the modulus mismatch between the inclusion and the martensite matrix. The stress concentration is postulated to produce cracks and plastic deformation. Schlicht et al. proposed that, in addition to the high stresses for stress assisted carbon diffusion, cracks are necessary for butterfly formation because they provide carbon diffusion sinks. This may suggest a decarburization mechanism. However, if decarburization were the ultimate cause, it would be expected that the white etching features would occur on both sides of the microcrack, which is not typically the case.

Because of the proposed necessity of a crack for the formation of butterfly WEA wings, it has been hypothesized that the formation of DEA prior to butterfly formation will suppress the number and size of butterflies that form [21]. This is thought to occur because localized plastic deformation associated with DEA formation reduces incompatibility stresses and strains around inclusions, lowering the stress concentration, and thus the propensity to nucleate a crack at the interface.

Figure 2.8 Butterfly formed in 52100 RCF specimen around Al₂O₃ inclusion [35]. Etchant not given.
2.4 Variables Influencing Contact Fatigue Resistance

One of the difficulties encountered in understanding contact fatigue is the large number of variables which affect contact fatigue resistance. The variables include contact stress, geometry, material properties, inclusion sizes, inclusion types, operating temperature, lubricant type, lubricant additives, lubricant properties, extent of sliding, rotation speed, surface roughness, and material characteristics. Each must be carefully controlled to ensure that results are reliable. The difficulty in controlling each and every one has prevented a greater understanding of contact fatigue failure mechanisms and the contribution of each variable. Material characteristic variables introduced by carburizing include case depth, IGO, retained austenite, residual stress, and prior austenite grain size (PAGS). The effects of these variables on contact fatigue, as reported in the literature, are discussed below.

2.4.1 Inclusions and Steel Cleanliness

Previous research on bearing and gear contact fatigue has shown that the variable that is most influential on the contact fatigue resistance of hardened gears is steel cleanliness; where steel cleanliness refers to nonmetallic inclusions [36–38]. Alumina inclusions are known to be the most detrimental to contact fatigue [25]. Sulfides, especially manganese sulfides, have been shown to have a less pronounced effect on contact fatigue of bearings steels, presumably due to their relative softness and deformability. Work by Hashimoto et al. [39] showed that in the absence of oxides, rolling contact fatigue life was affected by sulfide size and orientation with respect to the rolling direction. Cracks were observed to nucleate at the tips of the sulfide inclusions and propagate parallel to the rolling direction.
2.4.2 Case Depth

Case depth has been shown to be an important consideration for the resistance of carburized steel to bending fatigue and wear [40–43]. O. Asi et al. [43] showed that as the case depth of carburized SAE 8620 increased from 0.76 mm to 1.49 mm the bending fatigue limit decreased. The authors reasoned that increasing the case depth increased the depth of IGO and amounts of non-martensitic transformation products which both adversely affect the compressive residual stress distribution. Genel et al. [40], in contrast, showed that increasing case depth caused the fatigue strength of carburized 8620 to increase. The case depths ranged from 0.7 to 1.0 mm in the study. It is thought that there may be an optimal maximum case depth which increases the fatigue resistance of carburized 8620, although this optimal case depth is also application dependent (optimal case depth depends on part size, resulting residual stress, and hardness). Above this maximum the fatigue resistance appears to drop. Izciler et al. [41] showed that increasing the case depth of SAE 8620 increase the abrasive wear resistance. A possible explanation for the behavior was not given.

The effect of case depth on carburized gear steel contact fatigue resistance has not been studied. However, case depth is known to be an important consideration to prevent case crushing or subsurface initiated macropitting [21]. Case crushing occurs when the applied shear stress profile exceeds the shear strength profile of the carburized case/core interface. An example of case crushing along with the stress and strength profile schematic which can produce case crushing is shown in Figure 2.10. Figure 2.10 shows a case hardened specimen which failed by case crushing as well as a schematic illustration of the shear stress and strength profiles that can lead to case crushing. Increasing the case depth can help prevent case crushing and subsurface macropitting by ensuring that the shear strength of the case is always greater than the shear stress profile due to the contact.

2.4.3 Intergranular Oxidation

The effects of carburizing temperature and carburizing method on RCF resistance of SAE 4120 and 4320 were studied by Bykowski [44]. The carburizing conditions studied were three gas carburizing treatments at 899°C, 927°C, and 1010°C (1650°F, 1700°F, and 1850°F), a gas carburizing treatment at 1010°C (1850°F) followed by reheating to develop grain refinement, and vacuum carburizing at 1010°C (1850°F). RCF tests were carried out using a Federal-Mogul ball-on-rod rolling contact fatigue apparatus. The test rig was modified so that five 52100 hardened and ground ball bearings applied a radial force sufficient to develop a nominal Hertzian contact stress of 5.4 GPa. Each test was lubricated by dripping synthetic oil onto the bearings. The test specimens were rotated at 3600 RPM resulting in a loading frequency of 300 Hz. The results of the study are given in Figure 2.11. Bykowski observed a large increase in RCF resistance in the vacuum carburized samples. It was concluded that the lack of IGO in the
Figure 2.10 (a) Carburized cylindrical specimen which failed by case crushing. (b) Schematic of how stress and strength gradients can interact to create subsurface macropitting and case crushing.

Figure 2.11 Mean life and 95% confidence interval of 4120 and 4320 carburized RCF specimens. Adapted from work of Bykowski [44]. 5.4 GPa, pure rolling tests conducted using a Federal-Mogul ball-on-rod RCF machine.
vacuum carburized samples was the primary contributing factor to the increased contact fatigue resistance. The IGO present in the gas carburized samples was suspected to be the primary failure initiation site [44].

2.4.4 Retained Austenite

Due to the high carbon content of the austenite during carburizing, even at room temperature some austenite in carburized steels is stabilized and will not transform to martensite. This austenite is referred to as retained austenite (RA) [15]. RA has been shown, typically, to be beneficial to contact fatigue resistance, especially in the presence of debris denting or under contaminated lubrication and low lubrication conditions [45]–[49]. Work was conducted by Dong et al. [47] to investigate the effect of RA on rolling-sliding contact fatigue resistance. Tests were conducted at Hertzian stresses of 2.8 and 3.0 GPa and slide ratios of 20 percent. The steel used was 18Cr2Ni4W (0.18% carbon, 1.5% chrome, 4.25% nickel, and 1.0% tungsten). Heat treatments were applied to develop different levels of RA, from seven to fifty percent, through increased surface carbon content from carburizing, as well as though cryogenic treatments after carburizing. The samples having the higher amount of RA performed better in rolling sliding fatigue testing. Strain induced martensite was observed in the microstructures after testing (Figure 2.12) along with an increased surface compressive residual stress and hardness. It was postulated that the increased compressive residual stress and hardness due to RA transformation led to the increased contact fatigue resistance [47]. Roache et al. [49] showed that increasing RA improved the pitting fatigue resistance of bearings having artificial indentations. It was concluded that the RA increased the steel damage tolerance [49].

RA has also been shown to be detrimental to contact fatigue resistance in other conditions. One condition in which RA may be detrimental is when dimensional stability is of importance [21]. If the RA transforms during the operation of a component requiring high tolerance, the transformation to strain induced martensite results in a volume expansion that may result in distortion. The distortion can cause high stresses, excessive noise, and vibration [21]. RA is relatively soft and has poor wear resistance. Therefore, from a wear resistance perspective RA is not desirable. An excessive amount of RA will also lower the material resistance to fatigue initiation [21].

The nickel content of carburized steel is also an important consideration in regard to RA and material toughness. Nickel is an austenite stabilizing alloying element, though far less potent than carbon, and can increase the RA content [1]. RA increases the toughness of steel. Also, nickel by itself may have an effect on material toughness besides contributing to RA content. It is well known that the addition of nickel to a steel leads to improvement of fracture toughness by reducing susceptibility to cleavage fracture [50]. Possible improvements in toughness of carburized steels have been shown by increasing the
nickel content [51]. A clear explanation of the effect of nickel on contact fatigue resistance has not been proposed.

Figure 2.12  Micrographs of high RA case of 18Cr2Ni4WA alloy subject to rolling-sliding contact fatigue. (a) Before testing, white areas are RA and black are plate martensite. (b) After testing showing deformation induced martensite (increased amounts of dark etching features). (c) Re-plotted figure from [47] showing case RA profile before and after testing.

2.4.5  Residual Stress

During quenching from carburizing temperatures, residual stresses are developed which favorably affect fatigue resistance of carburized steels [1]. The compressive surface residual stresses formed in the case are due to the martensite start (Ms) temperature gradients developed by the carbon profiles resulting
from the carburizing treatment [45, 46]. The carbon content is greatest at the surface in the case which means that the Ms is lowest in the case. When a carburized component is quenched, the temperature decreases below the Ms at some point below the surface in the core. The interior transforms from austenite first. The surface and case temperature fall below the Ms and transform to martensite at some time after the transformation of the core. Because of the expansion associated with the martensitic transformation of high carbon austenite and the restraint from the transformed interior, the case of the component is put into a state of compression [45, 46]. As mentioned above, residual stresses can also be modified during contact fatigue testing presumably due to strain induced martensite formation. A schematic of this concept from the work of Voskamp et al. [54] is given in Figure 2.13.

![Schematic of alterations to residual stress profile due to retained austenite deformation induced transformation to martensite after rolling contact stress cycling on the order of 10^7 to 10^9 according to the results of Voskamp et al. [54].](image)

The compressive residual stress induced by proper carburizing has been shown to increase the contact fatigue life of bearings and gears [55]. The residual stresses can influence the maximum Hertzian shear stress acting on a contact material volume according to Equation (2.2) [21].

\[
\tau_r = -\tau_{oct} - \frac{1}{2} (\pm S_r)
\]

where \(\tau_r\) is the maximum shear stress modified by the residual stress, \(S_r\), and \(\tau_{oct}\) is the calculated shear stress. \(S_r\) can be positive or negative if the residual stress is tensile or compressive, respectively. It is thought that the compressive residual stress decreases the rate of fatigue crack initiation and growth.
leading to increased fatigue lives [21]. Batista et al. [56] suggested that residual stresses have a greater influence on impeding fatigue crack growth than on crack initiation.

2.4.6 Prior Austenite Grain Size

The true effect of the PAGS on the contact fatigue resistance of carburized gear steel has not been conclusively determined. Conflicting results exist [57–59]. Ooki [58] concluded that the contact fatigue life increases with decreasing PAGS. Based on the assumption that microstructure change associated with stress assisted carbon diffusion controls contact fatigue performance, Ooki suggested that a finer grain size retards carbon diffusion with grain boundaries acting as diffusion barriers, which leads to increased fatigue resistance. Liu et al. [59] also concluded that PAGS refinement leads to an increase in rolling contact fatigue resistance by increasing the case hardness. Conversely, Baughman [57] concluded that a decrease in the PAGS leads to a decrease in the $L_{10}$ life (the life at which 10 percent of samples are expected to fail). No satisfactory explanation for this behavior was given. It has also been shown that a finer PAGS improves the bending fatigue resistance of carburized steel [60]. Wise et al. [60] speculated that the increased tortuosity of the crack fracture path associated with finer grains was partially responsible for the increased fatigue resistance.

2.4.7 Tribology

An important consideration for RSCF is tribology. Tribology is the science of interacting surfaces in relative motion including the study and application of the principles of wear, friction, and lubrication. Gear and bearings systems are lubricated to decrease friction and wear in addition to providing some temperature control. Based on lubricant properties, the temperature of the contact environment, the contact load, and the geometry of the contacting bodies, a specific fluid film thickness is developed that represents the theoretical spacing between the contacting bodies. Of course, no surface is perfectly smooth. The micron and nano scale surface features of a gear tooth or bearing ball or raceway due to machining and polishing are referred to as asperities. The fluid film thickness relative to the combined asperity height of the contacting bodies defines the lambda ratio [58, 59]. This lambda ratio has been shown to be an important consideration for contact fatigue, especially when predicting the life of contacting components. When the lambda ratio is less than 1.0, asperity contact will occur and the chance of surface distress related failures including micropitting, macropitting, scuffing, and wear increase. Below a lambda ratio of about 0.8 there is little added protection from lubrication as shown in Figure 2.14. Figure 2.14 shows the increase in the fatigue life relative to increasing lambda ratio. Significant increases in the contact fatigue life of lubricated contacting components are not realized until the lambda ratio exceeds 2.0 or 3.0 [20, 34].
Figure 2.14  Schematic of effect of the lambda ratio on contact fatigue L_{10} life normalized to the maximum life. Adapted from [37].

2.4.8  Sliding

Sliding motion is developed during gear contact as the driving gear tooth contacts the driven gear tooth [60, 61]. The first point of contact occurs below the pitch line of the driving gear tooth, otherwise known as the dedendum. Conversely the initial point of contact on the driven gear tooth occurs above the pitch line in the tooth addendum. The pitch line is defined as the singular point on the gear tooth profile where pure rolling occurs. The most severe sliding (highest slide to roll ratio) occurs at the beginning and the end of the contact. The extent of sliding decreases as the tooth profiles roll/slide toward their respective pitch lines. The driving gear tooth experiences negative slide, that is, the sliding direction is opposite to the rolling direction. The driven tooth experiences positive slide because the rolling and sliding motions are in the same direction. After the gear teeth roll past their pitch lines during contact the positive and negative sliding behavior is reversed. The driving gear is contacted on its addendum and experiences positive slide and the driven gear is contacted on its dedendum and experiences negative slide. This concept is shown schematically in Figure 2.15. Negative sliding always occurs in the tooth dedendum [63].
Sliding is known to decrease contact fatigue lives [64–68]. The primary mechanism is related to the negative sliding experienced by a gear tooth below its pitch line in the dedendum. Higher stresses are encountered because the surface material is being rolled in one direction and pushed in another. The combination of pure rolling and traction forces alters the subsurface stress profile by increasing the maximum shear stress and moving the location where it occurs closer to the contact surface [64]. For this reason, contact fatigue damage is usually located in the dedendum of the gear tooth. Another reason why sliding decreases contact fatigue resistance was proposed by Kim et al. [68]. Kim proposed that with sliding, the number of stress cycles experienced locally by individual surface asperities increases for each contact cycle. This occurs because the asperities slide past each other and interact with more surface defects than they would if pure rolling was occurring and each asperity only interacted with one point on the other contacting body. Micropitting and cracking are therefore more likely to develop sooner with the increased number of asperity interactions [68].

2.5 **Shakedown**

During contact fatigue, plastic flow often occurs due to the Hertzian stresses. The plastic flow evident during contact fatigue is unlikely to be the result of a single loading cycle; rather it is an accumulation of strain developed over some period of the contact life. One source of this plastic deformation results from the shakedown process. Shakedown is the process where a loaded contact body
which deforms plastically or by wear initially during cyclic loading reaches a steady state in which the material response to additional loading cycles is perfectly elastic [69]–[72]. The initial cyclic plastic flow is referred to as ratcheting [72]. There are multiple sources which contribute to shakedown. One shakedown mechanism is the development of residual stresses either from the initial plastic deformation or from the formation of strain induced or stress assisted martensite from RA [66, 67]. Another mechanism is the strain hardening of the material to raise the elastic limit [66, 69]. The last is geometric changes of the contact bodies from either plastic deformation or wear which acts to reduce the level of the applied stress [66, 69]. Kapoor and Johnson [69] speculated that the plastically deformed profile in the steady state will approach the form which will carry the maximum load without exceeding the elastic limit. It was found that with sufficiently high load, a point contact geometry tends toward a line contact geometry as the number of loading cycles increases as shown in Figure 2.16. Figure 2.16 shows the evolution of the contact area between a steel roller and a cylinder sample with increasing contact cycles. The contact patch geometry changes from an ellipse (point contact) to being more rectangular (line contact). Schematic and graphical representations of geometrical and hardening shakedown are shown in Figure 2.17. In the hardening shakedown condition (Figure 2.17a), the material yield strength increases with increasing loading cycles. In the geometrical shakedown condition (Figure 2.17b), the applied stress decreases with increasing loading cycles (the applied load remains constant and the contact area increases). The importance of shakedown in the development of a steady state run-in condition on increasing contact fatigue resistance of carburized gear steel was shown by [73]. The authors indicate that the run-in condition helps to prevent fatigue crack initiation.

Figure 2.16 Change of contact area with cycles during shakedown for two steel bodies in contact (roller on cylinder). Shown are impressions on carbon paper made by compressing the paper between the contacting bodies at increasing number of contact cycles [69].
2.6 Failure Modes in Contact Fatigue

During the life of a component which experiences contact fatigue (bearing or gear tooth), there are several different failure mechanisms observed. The modes of failure can lead to excessive noise and vibration or subsequent total failure of the mechanical system. Scuffing of the surface can occur due to poor or inadequate lubrication. Wear occurs due to the interaction of the bodies sliding over each other, as-well-as foreign debris being caught in the contact zone. Pitting occurs during contact due to surface and subsurface originated cracking from cyclic contact stresses.

![Schematic and graphical representations](image)

Figure 2.17 Schematic and graphical representations of conditions leading to shakedown in contact fatigue. (a) Geometrical changes from plastic deformation leading reduction in applied shear stress. (b) Hardening leading to increase in yield strength. Black line represents point/line of contact. The hatched white area represents the portion of material where yielding is possible. Cycle A < cycle B < cycle C.
2.6.1 Scuffing and Starved Lubrication

Scuffing can be defined as a sudden rise in friction, contact temperature, vibration, and noise resulting in surface roughening through severe plastic flow and loss of surface integrity [74]. Ajayi et al. [74] present an explanation for scuffing as an increase in the rate of thermal softening until it surpasses the rate of work hardening. The thermal energy for softening can be supplied by frictional heating from starved lubrication [75]. The evolution of scuffing of hardened 4340 steel observed in SEM micrographs is presented in Figure 2.18. Figure 2.18a shows the surface microstructure prior to scuffing. Subsurface plastic flow is evident and increases in depth as scuffing occurs in Figure 2.18b.

The influence of lubricant starvation on the traction (friction) coefficient in contact loading was studied by Querlioz et al. [75] using a Mini Traction Machine (MTM) which rolls and slides a 20 mm diameter steel ball against a flat steel disc of known roughness. The amount of oil added initially to the contact zone was varied and the traction coefficient was measured over time. Figure 2.19a illustrates the change in traction coefficient over time for different amounts of lubricant during testing using the MTM machine. The results show that the traction coefficient is lowest for a fully flooded contact, and the time to reach the maximum traction coefficient as well as the magnitude of the steady state traction coefficient increases as the amount of lubricant decreases [75]. Contact fatigue tests using a disc-on-disc tester were also conducted by the authors to evaluate the effect of lubricant flow rate on fatigue life of a steel-on-steel contact containing a surface dent to accelerate failure. The testing results are summarized in Figure 2.19b. The authors concluded that there was a significant increase in contact fatigue life for increasing lubricant flow rates.

![SEM micrographs of scuffing progression in hardened 4340 steel](image)

Figure 2.18 SEM micrographs of scuffing progression in hardened 4340 steel (a) prior to scuffing and (b) after significant scuffing had occurred. The white arrow indicates the plastic flow near the surface. Scuffing occurred at a test load of 205 N (46 lbf) [74].
2.6.2 Abrasive Wear

Gears are often manufactured in such a way that it is geometrically tolerable, if not favorable, for some wear to occur initially during the first stage of operation to improve surface conformity [76]. Excessive wear, however, is undesirable. Besides adhesive wear (related to scuffing discussed above), the second wear mechanism that occurs in contact fatigue is abrasive wear. Two different types of abrasive wear can occur during contact fatigue. The first is two-body abrasion. Two-body abrasion occurs when a hard sharp feature on one body ploughs through the second body [61]. Two-body abrasion occurs in contact fatigue due to the interaction of surface asperities, especially if one of the bodies is harder than the other. If the wear is caused by a rough, hard particle trapped between the contacting bodies, it is referred to as three-body wear [61]. Three-body wear occurs in contact fatigue either due to foreign debris present in the lubricating oil or if a small piece of material from one of the bodies (worn asperity or micropit) flakes off and enters the contact zone.

Carburizing has been shown to increase the wear resistance of components by increasing the surface hardness [15]. Studies have also shown that an increase in the case depth produced during gas carburizing of 8620 gear steel resulted in a decreased wear rate. The results may have been influenced by an increased hardness associated with a deeper carburized case [41]. RA, being a softer microstructural constituent in carburized cases, is usually detrimental to steel abrasive wear resistance [14, 73]. Cryogenic
treatment of carburized cases exhibiting excessive RA causes much of the RA to transform to martensite. The transformation increases the case hardness and compressive residual stress leading to increased wear resistance as shown in Figure 2.20 [14, 73]. Figure 2.20a and Figure 2.20b show the decrease in wear for different sliding velocities resulting from cryogenic treatment of carburized En 353 to reduce RA content at test loads of 80 and 60 N, respectively.

![Wear rate measured after testing carburized En 353 subject to different levels of cryogenic treatment to force RA transformation. Tests conducted for 720 seconds according to ASTM 99-95a [78]. Wear results for tests conducted at (a) 60N (13.5 lbf) and (b) 80N (18.0 lbf). Reproduced from [77].](image1)

**2.6.3 Micropitting**

Micropitting, in this work, is defined as micro-scale pitting. Micropitting originates due to damage from rolling or rolling-sliding contacting metal surfaces which lead to microcracks that may grow and form micropits. Micropitting has been reported to be a gradual damage mechanism influenced by surface finish and lubrication (tribology) [21]. The micro-Hertzian contact stresses associated with localized asperity interactions are much higher than those calculated by a nominal macroscopic Hertzian stress analysis. However, they decrease in magnitude rapidly below the surface and do not affect the nominal contact stress [79]. Because of the local high shear stresses, the asperities are plastically deformed leading to a relatively smooth contact surface. This surface material is heavily deformed and with further cyclic stressing the ductility can be exhausted leading to microcracking and subsequent micropitting [20, 72]. Microcracks associated with micropitting are characterized by relatively shallow propagation depths around 2 to 13 µm deep (rarely up to 25 µm). The cracks propagate parallel to the
contact surface [80]. The presence of micropits, especially in combination with tractive interfacial stresses (such as from sliding), can lead to the premature formation of macropits [81].

2.6.4 Macropitting

There are two main types of pitting which occur due to cyclic contact loading: subsurface-origin pitting and surface-origin pitting [21]. Subsurface-origin pits result usually from defects in the bulk material such as inclusions, which are located at or above the depth of maximum shear stress. Many branching subsurface cracks are formed around an inclusion and apparently tend to propagate most rapidly perpendicular to the rolling direction, creating an elliptical shaped pit having steep or vertical walls [21]. The main variables that control subsurface pits are Hertzian shear stress level, material fatigue resistance, defect location, and defect size or severity [21].

Surface-origin pits are caused by surface defects at or near the surface of the material being cyclically stressed. Their formation is aggravated by any kind of tractive force from friction and sliding. These defects include scratches, machining marks, dents, micropits, and surface discontinuities. Surface-origin pits exhibit a shallow angle to the contact surface at the entrance, an arrow-head configuration pointing in the rolling direction, along with presence of a visible surface defect, or proximity to a stress concentrating geometrical aspect such as a sharp edge or corner [21]. Crowning of contacting surfaces has been shown to prevent geometrically related pitting [21]. The advanced stages of surface-origin pits exhibit brittle fracture. Fracture propagation at the late stages of pitting is rapid. The depth and size of the pits are reportedly not related to the contact stress profile [21].

Surface originated crack growth, leading to macropitting (or micropitting), may be aided by hydraulic pressure resulting from oil penetrating into the crack as proposed by Way [82] and supported by the work of Michau et al. [83]. It was suggested that the negative sliding acts to open a surface originated crack allowing lubricant to flow into the crack. As the load passes over a cracked surface, a crack is forced shut, enclosing, and pressurizing the liquid inside. The pressure inside of the crack serves to develop Mode I type crack tip opening which may aid crack propagation. It is proposed by Kaneta et al. [84] that the Mode I opening force is greatest when the crack is oriented at some angle to the surface and not perpendicular, potentially explaining why perpendicular contact fatigue cracks are seldom observed.
CHAPTER 3: EXPERIMENTAL PROCEDURE

3.1 Material Selection

The two materials that were selected for the RSCF study were SAE (Society of Automotive Engineers) steel grades 4120 and 4320. These steels were selected for three study objectives. First, both are commonly used in the heavy construction and agriculture vehicle industries as gear materials. Second, the compositional differences between the two gear steels may accentuate microstructural differences (e.g. IGO) which may contribute to differences in RSCF resistance. Lastly, carburized 4120 and 4320 have been used in previous ASPPRC work which investigated rolling contact fatigue (RCF) and rolling-sliding contact fatigue (RSCF). Correlations between current and past results were desired.

4120 is classified as a chromium-molybdenum steel and 4320 is classified as a nickel-chromium-molybdenum steel [85]. The chemical compositions (reported by the producer) and nominal alloy contents based on SAE specifications [86] are given in Table 3.1. Both 4120 and 4320 have similar hardenability utilizing alloying additions of nickel (in 4320), chromium, manganese, and molybdenum. Each of these elements, along with carbon, contributes to the stabilization of austenite during quenching from carburizing temperatures.

Table 3.1 Reported chemical compositions and SAE specifications in weight percent of SAE steel grades 4120 and 4320 selected for study.

<table>
<thead>
<tr>
<th>wt pct</th>
<th>C</th>
<th>Mn</th>
<th>Si</th>
<th>Ni</th>
<th>Cr</th>
<th>Mo</th>
<th>Ti</th>
<th>Nb</th>
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<tbody>
<tr>
<td>4120</td>
<td>0.20</td>
<td>1.09</td>
<td>0.26</td>
<td>0.13</td>
<td>0.50</td>
<td>0.15</td>
<td>0.002</td>
<td>0.002</td>
</tr>
<tr>
<td>Spec.</td>
<td>0.18-0.23</td>
<td>0.90-1.20</td>
<td>0.15-0.35</td>
<td>N/A</td>
<td>0.40-0.60</td>
<td>0.13-0.20</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>4320</td>
<td>0.20</td>
<td>0.58</td>
<td>0.28</td>
<td>1.72</td>
<td>0.52</td>
<td>0.22</td>
<td>0.003</td>
<td>0.001</td>
</tr>
<tr>
<td>Spec.</td>
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<td>0.15-0.35</td>
<td>1.65-2.00</td>
<td>0.40-0.60</td>
<td>0.20-0.30</td>
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<table>
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<th>wt pct</th>
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<th>Cu</th>
<th>B</th>
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<tr>
<td>4120</td>
<td>0.004</td>
<td>0.026</td>
<td>0.0082</td>
<td>0.023</td>
<td>0.007</td>
<td>0.18</td>
<td>0.0002</td>
</tr>
<tr>
<td>Spec.</td>
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<td>N/A</td>
<td>N/A</td>
<td>0.040</td>
<td>0.035</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>4320</td>
<td>0.005</td>
<td>0.028</td>
<td>0.0100</td>
<td>0.021</td>
<td>0.009</td>
<td>0.21</td>
<td>0.0002</td>
</tr>
<tr>
<td>Spec.</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>0.040</td>
<td>0.035</td>
<td>N/A</td>
<td>N/A</td>
</tr>
</tbody>
</table>

*Specification values represent an acceptable range or maximum.

The difference in manganese alloying addition between the 4120 and 4320 was the first chemistry specific factor considered for alloy selection. Manganese is the main oxide-forming element resulting from exposure to the oxygen bearing species in the endothermic carburizing atmosphere. It was hypothesized that with increased manganese content the 4120 would exhibit a greater extent of intergranular oxidation (IGO) than the 4320. IGO has been shown to be an important factor in RCF. A
better understanding of the effects of IGO in RSCF was desired. The second element considered for alloy selection was nickel. Nickel was added to maintain the hardenability of the 4320 alloy having roughly half the manganese addition.

### 3.2 Specimen Sampling

The RSCF samples used for the contact fatigue study were machined from hot rolled 4120 and 4320 round bar supplied by The Timken Company. The bar stock was provided with outer diameter measurements of 5” (127 mm). The samples were machined from the bar stock by Mile High Machining in Aurora, CO. The sampling plan used for the 25.4 mm (1”) diameter by 304.8 mm (12”) long RSCF samples is shown in Figure 3.1. The exact specimen dimensions are presented below. The samples were taken from six locations equidistant from the bar stock center and tangential-coincident with the mid-radial position. This location was selected to minimize any centerline segregation effects due to bar solidification.

![Figure 3.1](image-url)  
(a) Front view detailing sampling outside of mid-radial position and (b) side view (not to scale).

### 3.3 Heat Treatment

The RSCF samples were carburized using two different methods. Vacuum or low pressure carburizing was performed at ECM USA Inc. The remaining samples were gas carburized by Chrysler. The target surface carbon content was 0.9 wt pct for all conditions. The target case depth was 1.5 mm (0.059”). For case hardened components the case depth was defined as the depth below the surface at which the hardness decreased to 50 Rockwell C-scale (HRC) [87].
3.3.1 Vacuum Carburizing

The vacuum carburizing treatment was selected based on the conclusions made by Bykowski [44]. Bykowski found that the absence of IGO due to vacuum carburizing led to a significant increase in RCF lives of 4120 and 4320 samples presumably due to the absence of IGO [44]. The vacuum carburizing treatment was included to determine if the same benefits observed by Bykowski in RCF could be translated to RSCF. The target case depth for vacuum carburizing was 1.5 mm (0.016”) to minimize the possibility of case crushing and the target surface carbon content was 0.9 wt pct.

The vacuum carburizing heat treatment consisted of several boost and diffuse steps. The samples were wired vertically into the fixture shown in Figure 3.2 and heat treated in production furnaces. The boost cycle occurred at a temperature of 1010°C (1850°F) and a carbon potential in the range of 2.0 to 1.5 weight percent. Each boost cycle lasted for 70 to 200 seconds. The carbon bearing gas used for the boost cycle was propane. After the boost cycle, a diffusion cycle was applied at 840°C (1544°F). The diffusion cycle operated under pure nitrogen gas for 150 to 400 seconds. The carbon potential applied during the diffusion cycle was 0.9. Five boost and diffusion cycles were utilized for the low pressure carburizing of the 4120 and 4320 bar samples. After the final diffusion cycle the bars were quenched using nitrogen gas at 20,000 mbar pressure from 840°C (1544°F) to 200°C (392°F) after which the nitrogen flow was halted. The samples were held for five minutes and then cooled to room temperature using nitrogen by restarting the nitrogen flow. After quenching, the samples were tempered at 150°C (302°F) for two hours and air cooled [88].

![Figure 3.2 Vacuum carburizing fixture used by ECM USA Inc. for vacuum carburizing of RSCF samples. Twenty-one 4320 samples shown wired into the fixture][88]
3.3.2 Gas Carburizing

A high temperature gas carburizing treatment was selected to match the vacuum carburizing temperature of 1010°C (1850°F) with the goal that the prior austenite grain size (PAGS) and microstructure would be comparable for the vacuum and gas carburized samples. The gas carburized RSCF samples would contain IGO and the effects of IGO in RSCF could be isolated. The target case depth for gas carburizing was 1.5 mm (0.016”) to minimize the possibility of case crushing and the target surface carbon content was 0.9 wt pct.

The gas carburizing was performed in a laboratory scale furnace by Chrysler [10]. The sample fixture method was not reported. The samples were heated to 1010 °C (1850°F) in an endothermic atmosphere having a carbon potential of 0.9 wt pct. The samples were held at this temperature for 3.5 hours stepped down to 843°C (1550°F), and quenched in 65.5°C (150°F) oil. After quenching, the 4120 samples were tempered at 176°C (350°F) for two hours and the 4320 samples were tempered at 190.5 °C (375°F) for two hours [10].

3.4 Rolling-Sliding Contact Fatigue Experimental Matrix

The testing plan used to investigate RSCF damage in carburized gear steels is presented in Table 3.2. The six material conditions (vacuum carburized 4120 and 4320, gas carburized 4120 and 4320) were subject to pitting fatigue evaluation using the RSCF testing machine at CSM. Up to six tests were performed to pitting failure depending on the availability of RSCF samples having acceptable levels of distortion. If enough samples were available, incremental RSCF tests were also performed. The RSCF test was suspended at predetermined numbers of cycles to investigate the evolution of damage due to RSCF that leads to pitting failure. Additionally, a pure rolling test using the same nominal testing conditions as the RSCF tests without the gear box engaged (no sliding) was conducted for each condition and then suspended at the average fatigue life measured in the failure RSCF tests. The nominal testing conditions for the failure and incremental tests are presented in the next section.

Table 3.2 RSCF experimental matrix.

<table>
<thead>
<tr>
<th>Test Type</th>
<th>Vacuum Carburized</th>
<th>Gas Carburized</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>4120</td>
<td>4320</td>
</tr>
<tr>
<td>Pitting</td>
<td>Up to 6 tests</td>
<td>Up to 6 tests</td>
</tr>
<tr>
<td>Incremental Test Suspended at</td>
<td>1000, 10,000, 100,000, 200,000, cycles</td>
<td>1000, 10,000, 100,000, 200,000, cycles</td>
</tr>
<tr>
<td>Pure Rolling Test</td>
<td>1 test suspended at average RSCF life</td>
<td>1 test suspended at average RSCF life</td>
</tr>
</tbody>
</table>

*Not enough samples available for incremental testing of gas carburized 4120 and 4320.
### 3.5 Rolling Sliding Contact Fatigue Testing Conditions

One of the goals of the RSCF testing conducted during the study was to perform fatigue tests with the a fixed set of nominal conditions to control as many testing variables as possible. The target nominal Hertzian contact stress calculated based on pure-rolling, static conditions was 3.2 GPa (464 ksi). The rotations per minute (RPM), or cycles per minute, experienced by the RSCF sample was 1000. The target slide ratio created by the gear box was negative twenty percent (the load roller surface velocity larger than sample surface velocity). The oil used for RSCF testing was an Exxon 254 Jet Oil lubricant used for previous work [1, 4]. The target oil lubrication temperature was 100°C (212°F). The target surface roughness for the RSCF sample and load roller were 0.3-0.4 and 0.4 µm roughness-average (Ra), respectively. The load rollers were machined from SAE 4130 and carburized to a case depth of 2 mm (0.079”). A summary of the RSCF nominal testing conditions is given in Table 3.3.

<table>
<thead>
<tr>
<th>RSCF Testing Parameter</th>
<th>Nominal Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hertzian Contact Stress</td>
<td>3.2 GPa (464 ksi)</td>
</tr>
<tr>
<td>Maximum Sample Eccentricity</td>
<td>±0.0254 mm (±0.001”)</td>
</tr>
<tr>
<td>Sample (Load Roller) RPM</td>
<td>1000 RPM (250 RPM)</td>
</tr>
<tr>
<td>Slide Ratio</td>
<td>-20 percent</td>
</tr>
<tr>
<td>Lubricant Type</td>
<td>Exxon 254 Jet Oil</td>
</tr>
<tr>
<td>Lubricant Temperature</td>
<td>100°C (212°F)</td>
</tr>
<tr>
<td>Sample Roughness</td>
<td>0.3-0.4 µm Ra</td>
</tr>
<tr>
<td>Load Roller Roughness</td>
<td>0.4 µm Ra</td>
</tr>
<tr>
<td>Sample Case Depth</td>
<td>1.5 mm (0.059”)</td>
</tr>
<tr>
<td>Load Roller Case Depth</td>
<td>2 mm (0.079”)</td>
</tr>
<tr>
<td>Run-Out Cycles</td>
<td>10 million</td>
</tr>
</tbody>
</table>

### 3.5.1 Nominal Hertzian Contact Stress and Depth of Maximum Shear Stress Calculation

The Hertzian contact stress or pressure is a complex function of applied load, contacting body geometries, and material properties [90–92]. An analysis based on pure rolling, static contact conditions was carried out to ensure that the nominal contact stress during RSCF testing was developed by an appropriate compressive load, and comparable to previous work [4, 8]. Using the nominal Hertzian contact stress calculations below, the Hertzian stress was calculated for the loading/geometry employed in this work. The analysis assumed that a uniform load distribution existed, deformation was elastic, loading was perpendicular to the contact surfaces, and the contacting body geometries are very large compared to the contact area (3.33 mm wide contact patch versus 152.4 mm load roller crown radius) [91]. The testing conditions satisfied all of these assumptions, and therefore Equation (3.1) was applied [91].
\[ \sigma_{\text{max,contact}} = \frac{3w}{2\pi ab} \]  
(3.1)

where \( w \) is the applied load in Newtons and \( a \) and \( b \) are the semi-major (a) and semi-minor (b) dimensions of the elliptical contact area calculated below in Equations (3.2) and (3.3). Dimensions “a” and “b” are shown schematically in Figure 3.3.

\[
a = \left[ \frac{6k^2EwR_s}{\pi E'} \right]^{1/3} \]  
(3.2)

\[
b = \left[ \frac{6EwR_s}{\pi kE'} \right]^{1/3} \]  
(3.3)

![Figure 3.3 Schematic drawing of (a) contacting bodies resulting in elastic, elliptical contact patch with dimensions shown in (b).](image)

The elliptical parameter, \( k \), can be calculated along with the variables, \( R_s \), \( E \) and the effective modulus of elasticity, \( E' \) using Equations (3.4) to (3.7), respectively.

\[
k = 1.0339 \left[ \frac{R_y}{R_x} \right]^{0.636} \]  
(3.4)

\[
R_s = \left[ \frac{1}{R_x} + \frac{1}{R_y} \right]^{-1} \]  
(3.5)

\[
E = 1.0003 + 0.5968 \frac{R_x}{R_y} \]  
(3.6)

\[
E' = \left[ \frac{1 - v_1^2}{E_1} + \frac{1 - v_2^2}{E_2} \right]^{-1} \]  
(3.7)

\( R_x \) and \( R_y \) are geometrical parameters calculated from the radial measurements of the RSCF samples and load rollers using Equations (3.8) and (3.9). \( R_{x1} \) and \( R_{x2} \) are the radii of the sample and load roller in the
transverse direction. \( R_y1 \) and \( R_y2 \) are the radii of the sample and load roller in the axial direction (\( R_y1 \) is assumed to be infinite due to the cylindrical geometry of the RSCF sample), and \( \nu_1 \) and \( \nu_2 \) are the Poisson’s ratios of the sample and load roller, respectively.

\[
R_x = \frac{R_{x1} R_{x2}}{R_{x1} + R_{x2}} \tag{3.8}
\]

\[
R_y = \frac{R_{y1} R_{y2}}{R_{y1} + R_{y2}} \tag{3.9}
\]

The nominal Hertzian contact stress for all tests was 3.2 GPa (464 ksi). Each test was performed using samples and load rollers having the same geometries and elastic constants (Young’s modulus of 205 GPa and Poisson’s ratio of 0.29). The contact load required to achieve 3.2 GPa contact stress based on pure-rolling, static conditions was calculated to be 13.162 kN (2959 lbf) [91]. This load was below the maximum design load of the RSCF machine of 17600 N (4000 lbf) [89]. A contact stress calculation program, HertzWin 2.2.1, was checked against the contact stress calculations presented previously and verified to produce accurate Hertzian contact pressures. The program was used subsequently for quick contact stress calculations. The depth of maximum shear stress (below the contact surface of the RSCF sample) was calculated to be 428 µm (0.0168”), calculated using the HertzWin program. For reference, the elastic contact radii, “a” and “b” (Figure 3.3), of the contact patch were calculated to be 3.33 mm (0.131”) and 0.589 mm (0.0231”), respectively.

3.5.2 Subsurface Stress State Analysis

The nominal Hertzian contact pressure develops a complex stress state in the subsurface of the contacting bodies [9, 10]. The stress state is equally important as the contact stress. The results of the calculation of the principal contact stress (\( \sigma_1, \sigma_2, \) and \( \sigma_3 \)) profiles in the subsurface of a contacting body (RSCF sample) can be translated into an applied maximum shear stress or Von Mises stress profile.

Two simplified calculations to determine the stress profiles are based on sphere-on-sphere contact (idealized as a circular contact area with a single point of maximum Hertzian stress) or cylinder-on-cylinder contact (idealized as a rectangular contact area with a line of maximum Hertzian stress) [9, 10]. These two cases represent the extremes of contact geometry types. The complex geometry utilized in this work lies between the resulting point contact and line contact stress profiles. Therefore, it was useful to determine both. Important assumptions were made regarding the dimensions and elastic contact area of the actual complex geometries of the load roller and RSCF sample. These assumptions are described below.

Sphere-on-sphere contact results in a circular elastic contact area having a maximum Hertzian stress located at a single point at the center of the circle. The stress decreases from the center toward the
outer circumference. Figure 3.4 presents a schematic of point contact, along with variables important for the stress analysis. To estimate the subsurface stress state due to the maximum contact stress at the center of the contact circle for the complex RSCF sample and load roller geometries, the sample was assumed to be a sphere having a 25.4 mm (1") diameter and the load roller was assumed to be a sphere having a 127 mm (5") diameter (the smaller dimension), leading to a higher estimated stress state than the estimated stress state of the complex geometry studied in this work. The maximum Hertzian contact stress and contact area half width, “b”, are assumed to be the same as calculated above. The methods used to calculate the stress state as a function of depth, z, are given in Equations [3.10] and [3.11] [95]. The stresses $\sigma_x$, $\sigma_y$, and $\sigma_z$ are assumed to be the principal stresses: $\sigma_1$, $\sigma_2$, and $\sigma_3$.

Figure 3.4 Schematic illustration of (a) sphere-on-sphere contact and (b) the resulting circular elastic contact area.

\[
\sigma_x = \sigma_y = \sigma_1 = \sigma_2 = -p_{\text{max}} \left[ 1 - \frac{z}{b} \tan^{-1} \left( \frac{b}{z} \right) \right] (1 + \nu) - \frac{1}{2} \left( 1 + \frac{z^2}{b^2} \right)
\]  

\[
\sigma_z = \sigma_3 = -\frac{p_{\text{max}}}{1 + \left( \frac{z}{b} \right)^2}
\]

where $p_{\text{max}}$ is the maximum Hertzian contact stress, $\nu$ is Poisson’s ratio, $z$ is the depth beneath the contact surface, and $b$ is the semi-minor contact half width.

Cylinder-on-cylinder contact results in a rectangular elastic contact area having a maximum Hertzian stress located along a line bisecting the rectangle. The stress decreases from the centerline toward the sides of the rectangle. Figure 3.5 presents a schematic of line contact, along with variables important for the stress analysis. To estimate the subsurface stress state due to the maximum contact stress at the centerline of the contact rectangle for the complex RSCF sample and load roller geometries,
the load roller was assumed to be a cylinder having a 127 mm (5") diameter (ignoring the crown radius). The crown radius was ignored leading to a lower estimated stress state than the actual stress state of the complex geometry studied in this work. The cylinder-on-cylinder estimation has been shown to be the best estimate of more complex contact stress states [94]. The maximum Hertzian contact stress and contact area half width, “b”, are assumed to be the same as calculated above. The methods used to calculate the stress state as a function of depth, z, are given in Equations (3.12), (3.13), and (3.14) [95]. The stresses $\sigma_x$, $\sigma_y$, and $\sigma_z$ are assumed to be the principal stresses: $\sigma_1$, $\sigma_2$, and $\sigma_3$.

\[
\sigma_x = -2 \nu p_{\text{max}} \left[ \sqrt{1 + \left(\frac{z}{b}\right)^2} - \frac{z}{b} \right] \quad (3.12)
\]

\[
\sigma_y = -p_{\text{max}} \left[ \sqrt{\frac{1 + 2 \left(\frac{z}{b}\right)^2}{1 + \left(\frac{z}{b}\right)^2}} - 2 \frac{z}{b} \right] \quad (3.13)
\]

\[
\sigma_z = \sigma_3 = -p_{\text{max}} \frac{1}{\sqrt{1 + \left(\frac{z}{b}\right)^2}} \quad (3.14)
\]

where $p_{\text{max}}$ is the maximum Hertzian contact stress, $\nu$ is Poisson’s ratio, $z$ is the depth beneath the contact surface, and $b$ is the semi-minor contact half width.

Once the principal stresses are known, the Tresca and Von Mises yield criterion can be applied to determine whether the applied stress profiles due to the complex stress states will result in yielding. The maximum shear stress (compared to the Tresca yield criterion) is given in Equation (3.15) and the effective stress (compared with the Von Mises yield criterion) is given in Equation (3.16) [20].
The maximum shear and effective stresses for both point and line contact are presented in Figure 3.6. Note that the vertical line at 0.428 mm (0.0168”), which represents the depth of maximum shear stress calculated using the HertWin program, corresponds very well with the maximum stresses for line contact. The close correspondence with the cylinder-on-cylinder contact confirms that it is a good estimate of the actual contact stress profile of the RSCF sample and load roller geometries.

\[
\tau_{\text{max}} = \frac{\sigma_1 - \sigma_3}{2} \tag{3.15}
\]

\[
\sigma_{\text{Von Mises}} = \sqrt{\frac{(\sigma_1 - \sigma_2)^2 + (\sigma_1 - \sigma_3)^2 + (\sigma_2 - \sigma_3)^2}{2}} \tag{3.16}
\]

Surface Profilometry

A WYCO 3D optical surface profilometer and a Veeco Instruments Vision 32 program were used to measure the surface roughness and wear track profiles. The profilometry was performed using vertical scanning interferometry (VSI). VSI has a surface height resolution of approximately 3 nm root-mean-squared for a single measurement and less than 1 nm using multiple averaged measurements on a smooth highly reflective sample. The range of VSI measurements is up to 500 µm. The surface profile is
measured by coherent white light which creates interference fringes when the surface to be measured is in focus\[96].

Scans were made at 5X magnification and a 1X field of view. Before making profilometry measurements, a 10.11 µm step standard was used to calibrate the profilometer to within ±0.5 percent error. The load roller profiles were measured using a 3x scan speed, single scan, 45 µm vertical scan length and 30 µm vertical back-scan length, and a modulation threshold of 0.1 to 1 percent. A total scan length of 6 mm along the axis of the load roller was made using the stitching function of the program. Four locations were scanned on the circumferentially ground surface of the load roller. The roughness was quantified after filtering out the tilt and cylinder terms of the scan. The crown profile was measured by filtering only the tilt term. The sample roughness was measured using a 3x scan speed, single scan, 15 µm vertical scan length and 15 µm vertical back-scan length and a modulation threshold of 0.1 to 1 percent. For each sample testing location (two per RSCF sample bar), four scans were performed. A total scan length of 10 mm along the axis of the sample was made using the stitching function of the Vision 32 program. The surface roughness measurement was made by filtering the tilt and cylinder terms using the filtering function of the Vision 32 software.

Similar profilometry scans were performed after RSCF testing. The VSI variables were left the same as mentioned above. The load rollers were scanned to monitor the change in surface roughness and crown profile as a result of RSCF testing. This was done for two reasons. First, it would give a better understanding of the surface roughness that existed at the conclusion of RSCF testing. Second, it would show the extent of grinding necessary to refinish each load roller for multiple RSCF tests, if necessary. The RSCF sample wear tracks were also scanned after RSCF testing. This was done to observe the morphology of the wear track at the conclusion of RSCF testing in terms of wear track depth and roughness. Vertical scan lengths up to 45 µm were needed in the stitching scans to measure the entire wear track depth. Scans were always made just ahead of the RSCF pit to measure the local wear track geometry associated with the pitting failure.

3.5.4  Nominal Lambda Ratio Calculation

Systems subject to contact such as bearings and gears are almost always lubricated. The lubricant helps to increase the life of the components. In the presence of oil or grease, a film is created between the contacting bodies. The extent of separation between the bodies due to the lubricant film properties and contact stress has been considered in the context of elastohydrodynamic lubrication (EHL) theory. An EHL term that is of great importance in RSCF is the lambda ratio, or the ratio between the thickness of the fluid film and the surface asperity height. A high lambda ratio reduces the contact between surface
asperities related to the surface roughness. By reducing the contact of the two bodies through fluid film separation, the friction and temperature of the contact are reduced leading to an increase in life.

The lubricant used in this study was a synthetic polyol ester based Exxon 254 Jet Oil. This oil meets the MIL-L-23699 specification and has the physical properties listed in Table 3.4

<table>
<thead>
<tr>
<th>Temperature (°C)</th>
<th>Viscosity (cSt)</th>
<th>Viscosity (Pa-s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>40°C (104°F)</td>
<td>26.4</td>
<td>0.0242</td>
</tr>
<tr>
<td>100°C (212°F)</td>
<td>5.3</td>
<td>0.00525</td>
</tr>
</tbody>
</table>

The fluid film thickness of the lubricating oil was calculated according to Equations (3.17)-(3.25). These equations are due to Dowson and Higginson for the fluid film thickness under line contact [97]. The minimum film thickness is

\[
h_{\text{min}} = \frac{1.63\sigma^{0.54}(\mu_0 V_e)^{0.7}p_n^{0.43}}{(X_f W_{nf})^{0.13}E_r^{0.03}} \tag{3.17}
\]

The lambda ratio is given by

\[
\lambda = \frac{h_{\text{min}}}{\sigma} \tag{3.18}
\]

where the composite roughness, \( \sigma \) (inch), is given by

\[
\sigma = \sqrt{\sigma_1^2 + \sigma_2^2} \tag{3.19}
\]

The surface roughness (inch Ra) values of the contacting bodies is given by \( \sigma_1 \) and \( \sigma_2 \). The reduced modulus of elasticity \( E_r \) (psi) is calculated according to

\[
E_r = 2 \left( \frac{(1 - \nu_1)^2}{E_1} + \frac{(1 - \nu_2)^2}{E_2} \right)^{-1} \tag{3.20}
\]

where \( E_1 \) and \( E_2 \) are the elastic moduli of body one and two bodies in psi. \( \nu_1 \) and \( \nu_2 \) are the Poisson’s ratios of the two contacting elements. The normal relative radius of curvature, \( P_n \) (inch) is calculated by

\[
P_n = \frac{P_1 P_2}{P_1 + P_2} \tag{3.21}
\]

\( P_1 \) and \( P_2 \) are the radius of curvature of the contacting bodies in inches. For this analysis the sample radius is \( P_1 \), is equal to 12.7 mm (0.5”) and the load roller radius. \( P_2 \), is equal to 63.5 mm (2.5”). The entraining velocity, \( V_e \) (inch/second) is given by

\[
V_e = V_{r1} + V_{r2} \tag{3.22}
\]

where
\[ V_{r1} = \omega_1 p_1 \]  
\[ V_{r2} = \omega_2 p_2 \]

where \( \omega_1 \) and \( \omega_2 \) are the angular velocities in rotations per second. The normal unit load is given by

\[ w_{Nr} = \frac{W_{Nr}}{L_{min}} \]

where \( W_{Nr} \) is the normal operating load (lbf) and \( L_{min} \) is the minimum contact length (inch). \( X_f \) is assumed to be 1 because the load applied during testing is assumed to be normal to each contacting body surface.

The other two terms from Equation (3.17) are the absolute viscosity, \( \mu_o \) (lb sec/inch\(^2\)) and the pressure viscosity coefficient, \( \alpha \) (inch\(^2\)/lb). These two terms are determined by inspection of Figure 3.7, which shows how the absolute viscosity (Figure 3.7a) and the pressure viscosity coefficient (Figure 3.7b) of a MIL-L-23699 lubricant decrease with increasing temperature. Again, the nominal testing temperature for the RSCF testing in this work was 100°C (212°F).

![Figure 3.7](image)

(a) Absolute viscosity versus temperature for select gear lubricants and (b) pressure-viscosity coefficient of MIL-L-23699 lubricants. Adapted from [98].

The result of the lambda ratio calculation according to Dowson and Higginson yields a fluid film thickness of \( 4.17 \times 10^{-7} \) inch. Assuming that the sample and load roller have the specified surface roughness listed above, the lambda ratio based on pure-rolling, line contact is 0.187. This value is low; therefore it suggests that significant asperity contact will occur during RSCF testing leading to shorter contact fatigue lives.
The analysis presented above does not account for the effect of sliding. Taniguchi *et al* [99] put forth a correction factor to the previously described method to account for the effects of sliding on the EHL film thickness. The correction factor is incorporated into the determination of the film thickness according to Equations (3.26) and (3.27).

\[ h_{\text{min}} = (1 - 3.47W^{0.47}B)h_{\text{Dowson-Higginson}} \]  

where

\[ W = \frac{F}{E'R_x^2} \]  

and B is the sliding to rolling ratio (-20 percent in the current work), F is the applied force in lbf, E’ is the effective Young’s modulus, and \( R_x \) is the principal radius of curvature of an equivalent ellipsoid in inches, same calculation as Equation (3.5). Based on this analysis the correction factor was calculated to be 0.98. This lowers the fluid film thickness only a small amount and does not have a large effect on the lambda ratio. The final lambda ratio calculated based on the nominal testing conditions was 0.183.

### 3.5.5 Percent Slide Calculation

One of the driving forces for this work was to conduct contact fatigue tests having both rolling and sliding contact to simulate the meshing of gear teeth. A gear system was designed that could be easily adjusted by changing the gear ratios (or possibly the sample to load roller diameter ratio) to create different levels of sliding. To calculate the percent slide of the RSCF sample, or surface velocity of the sample relative to the surface velocity of the load roller, gear ratio calculations were performed.

First, some basics of gear ratio calculations are presented. Each gear can be thought of as a thin, simple cylinder having a diameter equal to its pitch diameter (the distance from the gear center to pitch line on each gear tooth profile). Also, for two gears to be compatible they must have the same ratio of number of teeth to circumference [94]. When two gears are meshed together, the surface velocity, given by Equation (3.28), at each gear’s pitch diameter is equal. This represents a “pure-rolling” situation.

\[ V = \omega R \]  

where \( V \) is the surface velocity at the pitch diameter, \( \omega \) is the angular velocity, and \( R \) is the radial distance from the gear center to the pitch diameter.

In the case of the RSCF machine, the angular velocity of the sample is equal to the angular velocity of the smaller gear in the gear box. The load roller is “forced” to have the same angular velocity as the larger gear. If the pitch diameter of the small and large gear were equal to the diameters of the sample and load roller, respectively, then the slide ratio would be zero and pure rolling would occur. However, this is not typically the case. Because the smaller gear has a pitch diameter slightly larger than the RSCF sample (31.05 mm pitch diameter gear versus 25.4 mm diameter RSCF sample) and the larger gear has a pitch diameter smaller than the load roller (124.23 mm gear pitch diameter versus 127 mm load
roller diameter), the surface velocity of the load roller is forced to be slightly higher than the RSCF sample surface velocity. Envisioning the system from the point of view of the sample, rolling and sliding over the load roller, the sample experiences negative sliding. Negative sliding occurs when the rolling direction of a rotating body occurs in the opposite direction as the sliding of that body relative to a contacting surface.

An example of this situation is if a car is rolling in reverse and suddenly acceleration is applied in the forward direction and the tires all switch and roll/skid in the forward direction but the car is still traveling in reverse, the tires are experiencing negative sliding. Counter to this, from the point of view of the ground, the ground is experiencing positive sliding. It is important to define the reference point for sliding calculations.

The calculation to find the percent slide experienced by the RSCF sample is given by Equation (3.29).

\[
\text{Sample } \%\text{Slide} = \left( \frac{D1 \times D4}{D2 \times D3} - 1 \right) \times 100\% \tag{3.29}
\]

where D1, D2, D3, and D4 are the diameters of the RSCF sample, load roller, small gear pitch diameter, and large gear pitch diameter, respectively, as shown in Figure 3.8.

![Figure 3.8 Schematic of RSCF sample, load roller, and gears illustrating dimensions for the percent slide experienced by the RSCF sample due to the gear box.](image)

### 3.6 Rolling-Sliding Contact Fatigue Machine

The test facility used to simulate RSCF in this work was designed and built by students at the Colorado School of Mines. The design of the machine is relatively simple and is shown schematically in Figure 3.9. A 304.8 mm (12”) long by 25.4 mm (1”) diameter bar sample is gripped and rotated by a motor, pulley, and chuck system. The sample is coupled to a gear box which is also coupled to a shaft
supporting a crowned, steel load roller. The gear box induces sliding in addition to the rolling motion between the sample and load roller. The gear box can be disengaged to allow pure rolling tests to be conducted. A hydraulic system applies a compressive radial force (up to 17.79 kN or 4000 lbf) on the sample by the load roller. This force is countered by four, polymer-coated support rollers which contact the sample on either side of the axial position in contact with the load roller. The sample design (diameter equal to or greater than 25.4 mm or 1”) minimizes the effects of bending [89]. Lubricating oil that can be heated up to 100°C (212°F) is fed onto the surface of the load roller at an adjustable flow rate depending on the rotational speed selected. The oil is captured, filtered by magnets and a 5 µm filtration pump, reheated, and recirculated back to the contact area. The number of fatigue cycles and RPM’s are monitored using an optical sensor on the rotating main shaft. The vibration of the load roller is monitored using an accelerometer. When there is a large increase in vibration associated with pit formation the RSCF machine is shut off automatically. More information about the machine design can be found in Chapter 4 of this document and in the M.S. thesis of Davis [89].

![Schematic drawing of RSCF testing apparatus designed and built by students at CSM.](image)

### 3.6.1 Sample and Load Roller Geometry

The RSCF sample geometry including machining specifications is shown in Figure 3.10. The samples include a ¼” bore and ¼” keyway at each end. The bore is used in combination with a pin and retainer to prevent the sample from slipping in the chuck. The keyway is used to transmit torque to the gearbox. The features are included on both ends to allow two RSCF tests to be conducted on each bar sample. The location of testing is such that when the sample is reversed to conduct a second test, the first wear track does not contact the support rollers and the wear profile is preserved for subsequent analysis.

The load roller geometry including machining specifications is shown in Figure 3.11. There are two holes for 5/16” (7.94 mm) safety wiring bolts on the roller. These are used to mount the load roller to
the support shaft. The ¼” (6.35 mm) keyway is used to transmit torque from the support shaft to the load roller. These features were machined onto the uncrowned wheel prior to carburizing. After carburizing the crown profile was circumferentially ground onto the roller. The crown radius of 152.4 mm (6”) was

Figure 3.10  RSCF bar sample as machined before heat treating, including machining specifications and tolerances. All units in inches.

Figure 3.11  Load roller specifications for machining. The crown radius was ground after carburizing. All units in inches.
specified to develop the desired nominal Hertzian contact stress. The crown radius can theoretically be adjusted as opposed to the hydraulic load to change the contact stress. Also, it should be possible for the load rollers to be reground following RSCF testing to allow a load roller to be used for multiple fatigue tests, especially for incremental tests having fewer than 500,000 cycles. Assuming very minimal change in load roller profile due to testing, the regrinding should be considered for future work to reduce costs associated with RSCF testing.

3.6.2 Grinding to Correct Distortion of RSCF Samples

The bar samples exhibited varying extents of distortion due to non-uniform cooling rates after carburizing. The distortion was such that the samples could not be tested in the as heat treated condition (maximum eccentricity of ± 0.02” or 0.5mm). Two types of grinding were applied. First, the sample ends were ground to improve the alignment of the bars and minimize the amount of distortion (alignment grinding). The very ends were tolerance ground back to an outer diameter of 25.4 mm (1.000”) so that the samples could be coupled to the gear box using a double U-joint having an inner bore of approximately 25.4 mm (1.000”). The grinding specifications are given in Figure 3.12.

![Alignment and tolerance grinding specifications for carburized RSCF samples post carburizing. All units in inches.](image)

3.7 Material Characterization

The methods used for materials characterization included: microhardness traverses to measure carburized case depth and the hardness profile before and after RSCF testing, carbon analysis to determine the carbon profile from carburizing, inclusion analysis to quantify and qualify steel cleanliness, metallography to characterize the carburized microstructure and to identify microstructure changes from RSCF, grain size measurement by etching to reveal the prior austenite grain size (PAGS), scanning
electron microscopy (SEM) to investigate IGO depth, and x-ray diffraction to measure the retained austenite fraction and residual stress.

3.7.1 Carburized Case Depth and Hardness Profiles

Hardness measurements were made on polished, transverse cross sections of the carburized RSCF samples. Each sample was ground through 600 grit and polished through 1 μm diamond polishing suspension prior to hardness testing. A Vickers diamond indenter was used for the hardness measurements. Each indentation was made using a 1000 g load and a 10 second dwell time. Fourteen total measurements were made radially inward for each hardness traverse. The first measurement was made at 0.159 mm (0.00625”) below the surface. The first eight measurements were made 0.159 mm (0.00625”) apart. The six subsequent measurements were taken 0.318 mm (0.0125”) apart. Four traverses were made for each condition.

The hardness measurements in HV\textsubscript{1000} were converted to HRC using Equation (3.30) [100]. This equation can be applied in the Vickers hardness range of 240-1040 HV [100]. The case depth was measured as the distance beneath the surface at which the hardness fell to 50 HRC [87].

\[
HRC = 119.0 - \sqrt{\frac{2.43 \times 10^6}{HV}}
\] (3.30)

3.7.2 Carbon Profiles

Carbon profiles were determined for each condition using LECO analyzers. A carburized bar sample was first tempered in a controlled atmosphere to lower the case hardness to allow machining while at the same time preventing decarburization. Once the cylindrical samples were softened, they were circumferentially ground to target depths according to an Eleven Pass Method presented in Table 3.5. The filings from each grinding step were then analyzed for carbon weight percent. The carbon analysis was conducted by The Timken Company.

3.7.3 Inclusion Analysis

Inclusion analysis of the 4120 and 4320 alloys was performed by The Timken Company using the ASTM E45-13 Inclusion Ratings for Steel standard [102]. This standard categorizes inclusions into four types: type A are sulfides, type B are alumina inclusions, type C are silicates, and type D are oxides. Each is rated based on severity and grouped according to the inclusion width and diameter parameters (thin or heavy). The severity of the inclusion is based on the length at 100X magnification and ranges from 0.5 to 5.0.
Table 3.5  Eleven Pass Method used for carbon profile measurement performed by The Timken Company [101].

<table>
<thead>
<tr>
<th>Cut</th>
<th>Aim Total Cut Depth</th>
<th>Aim Stock Removal Per Cut, Per Side</th>
<th>Nominal Plotting Depth</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>mm</td>
<td>inch</td>
<td>mm</td>
</tr>
<tr>
<td>1</td>
<td>0.0635</td>
<td>0.0025</td>
<td>0.0635</td>
</tr>
<tr>
<td>2</td>
<td>0.1905</td>
<td>0.0075</td>
<td>1.1270</td>
</tr>
<tr>
<td>3</td>
<td>0.3175</td>
<td>0.0125</td>
<td>1.1270</td>
</tr>
<tr>
<td>4</td>
<td>0.4445</td>
<td>0.0175</td>
<td>1.1270</td>
</tr>
<tr>
<td>5</td>
<td>0.5715</td>
<td>0.0225</td>
<td>1.1270</td>
</tr>
<tr>
<td>6</td>
<td>0.9525</td>
<td>0.0375</td>
<td>1.1270</td>
</tr>
<tr>
<td>7</td>
<td>0.13335</td>
<td>0.0525</td>
<td>1.1270</td>
</tr>
<tr>
<td>8</td>
<td>0.9525</td>
<td>0.0375</td>
<td>1.1270</td>
</tr>
<tr>
<td>9</td>
<td>1.0795</td>
<td>0.0425</td>
<td>1.1270</td>
</tr>
<tr>
<td>10</td>
<td>1.2065</td>
<td>0.0475</td>
<td>1.1270</td>
</tr>
<tr>
<td>11</td>
<td>1.3335</td>
<td>0.0525</td>
<td>1.1270</td>
</tr>
</tbody>
</table>

Note: Stock removal per cut is measured per side (not diameter).

3.7.4 Metallography

Metallographic analysis was performed for each carburizing condition prior to testing to characterize the carburized case and core microstructures. Transverse metallographic samples were sectioned from carburized, non-RSCF tested samples. Each sample was ground and polished through 1 μm. The samples were then etched in picral immediately after polishing. The picral etchant was prepared using 100 ml ethanol, 4 g picric acid, and three drops of hydrochloric acid (HCl) to increase the etching response. The samples were etched by submerging the polished surface into the etchant for 5 seconds and then rinsing with methanol. The extent and quality of etching was observed using light optical microscopy (LOM). If necessary the samples were then re-etched for 3 to 5 seconds.

Metallography was also performed on chordal sections of the gas carburized samples to observe the near-surface microstructure containing intergranular oxides. Chordal sectioning was done by mounting the curved cylindrical samples with the curved cylindrical side down as shown in Figure 3.13. The samples were ground to reveal a rectangular area. The long edges of the revealed rectangle correspond to the very near surface microstructure. The samples were ground until a similar sized ground rectangular area (approximately 3 mm wide) was revealed for each condition, polished, and etched for 5 seconds in picral. The near surface microstructures were observed using LOM and field emission scanning electron microscopy (FESEM).
3.7.5 Grain Size Measurement

Metallographic samples for grain size determination were prepared as before taking extra care to prevent pitting from excessive time and force, particularly at the 1 µm polishing step. A prior austenite grain (PAG) etchant was prepared using 100 ml de-ionized water, 1 ml teepol to aid in grain boundary wetting, and enough picric acid to saturate the solution (roughly 5 grams). The solution was placed on a magnetic stirring hot plate and heated to 65°C. Three drops of HCl were added to enhance the etching response. Once all of the picric acid dissolved, the samples were etched. The etching procedure required some trial-and-error. Samples were usually submerged for 45 seconds to 2 minutes, cleaned with methanol, dried, and then lightly back-polished on a 1 µm pad. These steps were repeated until the grain structure was clearly visible. Etch pitting was common. To help reduce the prevalence of etch pitting, the samples were thoroughly cleaned using an ultrasonic cleaner. It was also found that a fresh batch of the saturated aqueous picric solution caused increased pitting. If the solution was allowed to sit for a few days to a week, the prevalence of pitting decreased. After etching, twelve micrographs were recorded at 200X magnification using LOM. Quantitative analysis of the PAGS was performed using the ASTM E-112 Average Grain Size Method [103].

3.7.6 Intergranular Oxidation

IGO was observed in the SEM after polishing samples to 1 µm. Backscatter SEM was used to image the oxides on the polished transverse section at 500X magnification. Ten micrographs were recorded of surface oxides for each condition. The IGO depth was measured by drawing a line parallel to the surface to identify the apparent oxide depth according to Figure 3.14. Figure 3.14a shows a typical SEM micrograph of the surface oxides and Figure 3.14b shows the line superimposed on the micrograph at the apparent depth of IGO penetration used to measure the characteristic IGO depth. Ten measurements
were taken per image using digitizing software which translates pixels into length. The characteristic IGO depth was determined by averaging the 100 measurements for each condition.

Figure 3.14 Procedure used to quantify the characteristic, average, maximum IGO penetration in gas carburized RSCF samples. (a) Original micrograph of surface IGO. (b) Line of the apparent maximum depth of IGO penetration placed “parallel” to the sample surface.

3.7.7 Retained Austenite Determination

X-ray Diffraction (XRD) was used to measure retained austenite (RA) profiles for each material heat treatment condition. The measurements were carried out by The Timken Company. A sample from each material was analyzed by XRD to measure diffraction patterns associated with each condition at the surface and then chemically thinned, re-measured, and scanned again to determine the RA fraction at the measured depth. Each XRD measurement was conducted using a 45 kV accelerating voltage and 40 mA. Filtered copper radiation was used. The resulting diffraction peaks were measured to determine the peak intensity and location. Equation (3.31) was then used to determine the retained austenite fraction [104].

\[
V_\gamma = \frac{1}{n_\gamma} \sum_{\gamma} I_{\gamma}^{hkl} R_{\gamma}^{hkl} - \frac{1}{n_\alpha} \sum_\alpha I_{\alpha}^{hkl} R_{\alpha}^{hkl} + \frac{1}{n_\gamma} \sum_{\gamma} I_{\gamma}^{hkl} R_{\gamma}^{hkl}
\]

where \(n_i\) is the number of peaks of the \(i\)th phase (austenite or ferrite), \(I\) is the integrated intensity of a specific \{hkl\} peak for an \(i\)th phase, and \(R\) is determined according to the peak location. Cullity provides
the methodology for determining these factors for austenite and martensite [105]. The (211) and (110) peaks for martensite, and the (111) peak for austenite, were used for the analysis.

3.7.8 Residual Stress

The residual stress profile for each carburized condition was measured in the same fashion as for RA using XRD and chemical thinning. The residual stress was determined using a \( \sin^2 \psi \) method [106]. This method correlates the lattice strain to residual stress in the \{200\} ferrite peak. Vanadium filtered chromium radiation was applied using an accelerating voltage of 45 kV and 40 mA. The lattice strain was plotted against \( \sin^2 \psi \). Linear least squares fitting determined the slope of the line having the minimum \( R^2 \) value. This slope was used with the Young’s modulus and Poisson’s ratio to determine the residual stress present. The analysis was performed by The Timken Company.

3.8 Failure Analysis

Failure analysis was conducted after RSCF testing. First, the individual wear track sections were cut from the bar sample, oiled, and contained in plastic tubing to preserve the failure features if analysis could not be performed immediately. Profilometry was performed on each wear track. Post-test roughness quantification was also attempted. However, the wear track surface profiles were scratched and dented due to pitted material entering the contact zone causing artificial damage not representative of the surface profile which existed prior to the pitting event. Knowing this, roughness measurements post RSCF testing were not thought to be accurate. The pits and wear track features produced during RSCF testing were imaged using SEM. The samples were sectioned according to the illustration in Figure 3.15. A transverse cut was made through the center of the RSCF pit. Metallography was performed as before to investigate changes in case microstructure due to RSCF testing.

3.8.1 Wear Track Morphology from Profilometry

The wear track depths were estimated quantitatively using optical profilometry. The profilometry scan was performed just ahead of the pit (approximately 2 to 3 mm). The pit “direction” was known from both the rolling direction and the characteristic arrowhead morphology of the RSCF pits (discussed in Chapter 6). The results of the scan were filtered to remove the tilt term and a two dimensional axial profile was extracted from the data. The two dimensional profile was compared to the original two dimensional profile measured prior to RSCF testing. A best fit parabolic curve was placed over the wear track profile. The distance between the base of the best fit curve and the centerline of the original surface profile was defined as the pitting location wear track depth. The width of the wear track was also measured using optical profilometry methods. The distance between the intersections of the best fit wear
track profile parabola and the original wear track centerline was defined as the wear track width. Figure 3.16 illustrates the best fit curve (curved, dashed line) and the associated width and depth.

Figure 3.15  Sectioning schematic of (a) wear track sectioned from RSCF bar sample, (b) sectioning plate through wear track and pit center, and (c) locations of transverse cross sections for microstructural and evaluation.

Figure 3.16  Quantitative characterization of (a) RSCF wear track (b) depth and width measured using optical profilometry. The parabolic, dashed line in (b) represents the estimated curvature of the wear track profile.
3.8.2 Fractography

Fractography was performed on the RSCF pits produced during each contact fatigue test. Fractographs of the RSCF pitting were taken using secondary SEM. Macro images of the pits were taken to characterize the overall pit morphology. The “pit tips” were also imaged at high magnification to investigate possible pitting initiation modes. The wear tracks were also investigated with SEM to characterize micropitting, wear track surface cracking, and possible wear modes.

3.8.3 Butterfly Feature Probability Analysis

A simplistic probability analysis was carried out on each material condition to attempt to relate the material properties and pitting resistance for each test condition to the likelihood of observing a butterfly feature around a non-metallic inclusion. This probability was thought to relate to the resistance to butterfly formation. Probability analysis was conducted by observing the transverse section of each wear track at 200X magnification using LOM. The number of non-metallic inclusions was counted along with the number of butterflies. Sulfide inclusions were excluded from the analysis as they were observed to rarely develop butterflies. The probability of butterfly formation was calculated according to Equation (3.32).

\[
P_{\text{butterfly}} = \frac{N_{\text{butterfly}}}{N_{\text{butterfly}} + N_{\text{no butterfly}}} \tag{3.32}
\]

where \(P_{\text{butterfly}}\) is the probability of finding a butterfly feature at a non-metallic inclusion, \(N_{\text{butterfly}}\) is the number of butterfly structures counted, and \(N_{\text{no butterfly}}\) is the number of inclusions without butterflies.

3.9 Contact Fatigue Apparatus Correlation Testing

Prior work at CSM investigated the pitting fatigue resistance of carburized gear steel under RCF conditions. The testing rig used was a Federal-Mogul Ball-on-Rod RCF (FM RCF) tester. A secondary goal of the present work was to attempt to correlate the contact fatigue behavior of the RSCF machine and the FM RCF rig under pure rolling conditions. The RSCF machine can produce a pure rolling condition when the gear box is disengaged. The pure rolling tests were conducted at a nominal Hertzian contact stress of 5.4 GPa. Samples for both the FM RCF and RSCF machine were machined out of SAE 4120 remaining from Bykowski’s work [44]. The ball bearings and load rollers used to apply the compressive contact forces were machined from 52100 grade 24 steel and through hardened. The FM RCF sample and ball bearing geometry required a radial load of 1055 N (238 lbf) to develop this stress. The RSCF machine was run at a hydraulic load of 13.39 kN (3010 lbf) with a redesigned load roller having a reduced crown radius of 20.32 mm (0.8”).
3.9.1 Federal Mogul Ball-on-Rod Rolling Contact Fatigue Machine

The FM RCF machine used for the correlation testing (and previous CSM work) was donated by the Timken Company. The four testing heads are shown in Figure 3.17. The testing rigs use a modified five ball bearing setup described in [44] and shown schematically in Figure 3.18. The radial load on the RCF sample was applied by clamping the 12.7 mm (0.5") diameter ball bearings in an upper and lower bearing race pressed into the aluminum plates of the testing rig heads. When these two aluminum plates were bolted together the load was applied to the sample by the bolts with the magnitude depending on the compression of the loading springs on the test heads. The calibration of the test head springs to ensure the

![Images of (a) FM RCF testing rig donated to CSM by The Timken Company and (b) one of four RCF testing heads on the RCF machine.](image)

![Schematic drawing (not to scale) of FM RCF sample and five ball bearing setup, (a) top view and (b) side view.](image)
proper load is applied is described below. The rotation speeds used for the FM RCF and RSCF machines were 3600 and 1000 RPM, respectively. The number of cycles per rotation of the FM RCF machine due to the five ball setup was 3.982 [107].

3.9.2 Federal Mogul Ball-on-Rod Sample Geometry

As mentioned previously, the samples used for the correlation testing were machined from 4120 bar stock. The samples used in the RSCF machine with the gear box disengaged were exactly the same as those used for RSCF testing. However, they were carburized to a target case depth of 0.9 mm (similar to the work of Bykowski and Davis) and no post heat treating grinding was performed to correct distortion. The FM RCF rod sample geometry is presented in Figure 3.19. The surface finish of both the RSCF and FM RCF samples was specified to be 0.4 µm Ra. The load rollers used for the RSCF test machine were ground to a surface finish of 0.3 µm Ra. The 12.7 mm (0.5”) 52100 ball bearings used for the FM RCF tests were finished to a 0.089 µm Ra roughness. The bearings were ordered off-the-shelf from the Delta Research Corporation.

Figure 3.19 FM RCF rod sample machining specifications.

3.9.3 Federal Mogul Ball-on-Rod Machine Calibration

The nominal 5.4 GPa Hertzian contact stress to be developed during the contact fatigue testing was created by the application of 1055 N (238 lbf) radially inward load with five ball bearings. This radial load was created by compressing the housing cups which contained the bearings by tightening the test head bolts completely. The load transmitted to the specimen by the ball bearings was controlled by the amount of compression imparted to the three, equidistant loading springs on the test heads. The springs were calibrated to apply the appropriate load using an indentation calibration method. First, a calibration curve was obtained by indenting an aged 2024-T4 aluminum rod with the same diameter as the FM RCF samples with polished 52100 bearings at incremental compressive loads ranging from 667 to 1557 N (150 to 350 lbf). The indentation was made using a simple loading jig [2, 20] inserted into a load controlled compression frame. The widths of the resulting ellipse indentations were measured as shown in Figure 3.20a resulting in the calibration curve shown in Figure 3.20b. The calibration curve was used to find the indentation geometry that matched the desired load.
After the required ellipse width was known, another 2024-T4 rod was inserted into the FM RCF test head to be calibrated with five polished ball bearings. The test head was clamped together by inserting a modified configuration of the test head (see Shutt’s work [108]) into a hydraulic hand press. A load of 800 lbf was applied for five seconds. The aluminum bar was then removed and the five indentations were measured. The springs on the test head were then adjusted meticulously until five, equal width ellipses having the correct geometry were produced by clamping the test head together. Adjustments to the springs were as fine as 1/16 of a turn to produce the desired force. More information on the calibration procedure can be found in [44, 108].
CHAPTER 4: TESTING MACHINE MODIFICATIONS

4.1 Introduction

The RSCF machine as it existed at the beginning of the RSCF investigation, presented challenges in conducting reliable and robust contact fatigue tests. The initial goal of the thesis project was to address several problematic aspects of the RSCF machine before fatigue testing and analysis could commence.

One of the most significant issues was related to the difficulty in aligning the 20” (50.8 cm) main shaft, chuck, 12” (30.5 cm) carburized bar sample, load roller and support rollers, and the gear box shafts. There were three, inexact ways to adjust the overall alignment to not only align the shafts to be parallel and axially coincident, but to also align the rotation of the sample to avoid a rotational eccentricity greater than ±0.001”. The alignment process required hours of tedious adjustments. The main 20” (50.8 cm) shaft also experienced wear and fretting where it contacted the two pillow block bearings. This wear and fretting eventually caused instability in shaft rotation leading to damage of the rest of the machine and invalidation of fatigue tests.

The RSCF sample design made the bars susceptible to bowing and distortion as a result of non-uniform thermal stresses during quenching after carburizing. The vacuum carburized samples exhibited the least distortion due to the uniformity of the gas quench process. The low temperature gas carburized samples exhibited some distortion. The high temperature gas carburized samples exhibited excessive distortion and only a few of the samples could be used. The distortion compounded the alignment issues mentioned above and led to increased machine damage and high load fluctuations.

A third design issue was the lubrication system. The lubrication system, initially, consisted of a ½ liter heated bath. This bath was filled and placed under the load roller. As the load roller rotated, it would pick up heated oil and bring it into the contact zone with the RSCF sample. A simple splash guard slipped over the sample at the contact zone to catch the oil and force it to flow back into the oil bath. The initial lubrication setup was unable to be fully sealed. Leakage was unpredictable and unavoidable. Only a small amount of oil needed to leak out of the bath/splash guard to cause the oil level to fall below the level of the bottom of the load roller, and thus starved lubrication contact could develop rapidly.

The gear box system also needed to be adjusted. The gear box, which was used to control the sliding ratio between the RSCF sample and load roller, was coupled to the sample and load roller shafts using solid shaft coupling systems. These couplings could tolerate maximum shaft axial misalignments of ±0.015”. During testing, the rigid couplings would cause the gear box to shake excessively increasing the machine vibration, noise, and wear. The oil in the gear box was the same lubricant used for the RSCF testing. It often leaked out of the ball bearing bores and needed to be replenished frequently. The bearing
bores in the gear box plates were also slightly too large and the bearings could be easily forced out of position which could cause excessive damage to the gears and the rest of the machine.

A final, minor issue was that the rubber belt used to rotate the main shaft would loosen leading to excessive vibration and noise. The belt loosening also meant that the RPM’s would begin to decrease and were not constant between tests leading to variations in imposed lambda values. Thus control of excessive vibration and a constant imposed shaft rotational velocity was needed.

4.2 Adjustable Chuck and Main Shaft

Wear and main shaft instability were addressed in two ways. The main shaft was remade by substituting hardened A2 tool steel for 1045 to improve the wear resistance. The concentric rotation was improved by inserting 0.003” stainless steel shims between the main shaft and the pillow block bearings. This eliminated the rotational instability; however the set screws in the pillow block bearings could no longer be used for alignment. The stainless steel shims would slip out of the block bearings during testing. To prevent shim slippage, two additional two-piece, 2” (50.8 mm) ID shaft clamps were added to the main shaft assembly shown in Figure 4.1. These clamps also prevented undesirable axial traveling of the main shaft which could both invalidate RSCF tests as well as cause damage to the RSCF machine.

![Double shaft clamp configuration on main shaft assembly of RSCF machine.](image)

Figure 4.1 Double shaft clamp configuration on main shaft assembly of RSCF machine. The arrows indicate the locations of the shaft clamps on either side of the pillow block bearings.
The original three jaw chuck was replaced using an adjustable three jaw chuck. The chuck back plate had to be redesigned to accommodate the new chuck. The advantage of the adjustable chuck is that it can be adjusted so that the rotation of the chuck can be centered even if the main shaft is spinning out of alignment. It can also be used to account for slight sample distortion. The chuck is aligned using four set screws according to the alignment procedure detailed in Appendix A. Figure 4.2 shows an image of the adjustable chuck installed onto the main shaft assembly and custom back plate. The upgrade to the adjustable chuck decreased the time required for sample alignment from hours to minutes.

Figure 4.2 Adjustable three jaw chuck installed in RSCF machine. Arrow points to one of four adjustable set screws for easy alignment.

4.3 Sample Alignment and Tolerance Grinding

As mentioned above, sample distortion after carburizing was common. The distortion needed to be corrected to allow the samples to be aligned in the RSCF machine. The extent of distortion was characterized as low, marginal, and excessive. Visual representations of the distortion levels are depicted in Figure 4.3. The samples with low distortion (Figure 4.3a) had run-outs of ±0.005” and did not necessary need to be alignment ground, however alignment grinding was still performed as a safeguard. The samples with marginal distortion (Figure 4.3b) had run-outs of ±0.020” and did require alignment grinding. The samples with excessive distortion (Figure 4.3c) were unusable for RSCF testing but could be used for material characterization.
Alignment grinding was performed by gripping the distorted RSCF sample in a lathe using the centers machined into the sample prior to carburizing. Samples were then rotated and the ends (gripped by the centers) were ground down, in the 3.188” regions specified in Figure 4.4, until they rotated with little to no eccentricity (± 0.001”). Some eccentricity would still be present in the center of the sample. Alignment grinding of the distorted samples allowed the ends of the samples which are gripped by the chuck and attached to the gear box, to spin “true” and reduce damage to the machine and ambient vibration during testing. The alignment grinding also reduced load fluctuations during RSCF testing resulting from rotation of the distorted sample. Alignment grinding is also relatively simple as compared to centerless grinding. Centerless grinding, which would have been the preferred machining method, could not be used because it would require re-machining of the sample bores and keyways.

Both the low and marginal distortion RSCF samples had to be tolerance ground at each end to ensure that the samples could be inserted into a 1.000” (25.4 mm) bore of the gear box double U-joints. The diameters of the samples after carburizing were as high as 1.015” (25.8 mm). Figure 4.4 shows the sample drawing of an alignment and tolerance ground RSCF sample specification provided to the machine shop.
Figure 4.4 Grinding specifications for alignment and tolerance grinding of distorted, carburized RSCF samples. All dimensions in inches.

4.4 Lubrication System

The lubrication system was redesigned to provide a reliable, continuous flow of filtered, hot oil with adjustable flow rates. A schematic and photograph of the lubrication system are shown in Figure 4.5. The previous bath/splash guard set up is described and shown in Davis’ 2011 thesis [89]. First, a portable, oil-pump/filter system was purchased (Serfilco portable oil filter). The pump has a flow rate of over 1 gallon per minute and is equipped with a 5 µm replaceable filter. Second, a stainless steel gravity feeding oil reservoir was designed and built. The reservoir included two heating elements, a float switch to automatically cycle the pump on and off, and a valve to adjust the gravity fed flow rate. The reservoir was insulated to minimize heat loss. Next, scaffolding for the gravity feeding reservoir was designed and installed onto the RSCF machine. A vibration resistant, guided dispensing nozzle was installed on the load roller head so that hot oil could be accurately dispensed onto the roller surface. Thermocouples were placed in both the gravity feeding reservoir and in the dispensing nozzle to allow the oil temperature to be controlled and monitored.

A very important consideration for the new circulating oil system was containment and return of the oil after it had passed through the contact zone. This part of the lubrication system consisted of three parts: a splash guard, an oil catch pan, drain, and return reservoir. The splash guard was constructed out of readily available plastic food storage containers that were cut to specific geometries that could be bolted onto the support head of the RSCF machine. The guards, along with large rubber seals, allowed the containment of splashing oil at the sample-load roller contact zone. The oil catch pan was installed below the load roller and support heads to capture any oil dripping down from the splash guard. The oil then
flowed into a drain which carried it to the return reservoir, from which it was filtered and pumped by the Serfilco unit back up to the gravity feeding reservoir.

In addition to the main 5 µm filtration system, magnetic filtration was also applied to capture ferrous fines resulting from any pitting and wear. The first magnets were placed around the drain and just below the contact zone in the oil catch pan. Large, high pull switch magnets were also placed in the return reservoir both around the return tubing and around the pump feed tubing. The magnets were an added precaution to prevent contaminated oil from reaching the contact zone.

![Figure 4.5](image)

Figure 4.5 (a) Schematic of lubrication system: (a) pump, (b) filter, (c) gravity feeding reservoir, (d) thermocouples, (e) heating elements, (f) float switch, (g) valve, (h) catch pan, and (i) return reservoir. (b) Image of lubrication system installed on RSCF machine.

4.5 Gear Box and Alignment

The redesigned gear box for the RSCF machine improved the robustness of the system, reduced vibration and noise, and reduced time and effort associated with alignment of the gear box with the sample and load roller. The original gear box design and coupling system can be found in Davis’ thesis [89]. The first change to the gear box design was to increase the center-to-center distance of the gears from 3.000” (76.2 mm) to 3.016” (76.6 mm) to match the pitch diameters of the gears. This change helped to reduce gear box noise and gear wear. The next alteration was the addition of a site glass to the gearbox so that the oil level could be monitored accurately during RSCF testing. Oil catch pans were installed beneath the four gear box bearings to prevent oil loss. The bearings would often fall out of the bores in the gear box plates due to improper tolerance requirements. Retainer plates were installed over the bearings to prevent them from falling out. These additions are shown in Figure 4.6 which shows the back (Figure 4.6a) and front (Figure 4.6b) view of the gear box.
The second aspect of the gear box that was improved was the coupling mechanism between the gear box shafts and the sample/load roller shafts. Instead of using shaft couplings which had very low tolerance for axial misalignment (shown schematically in Figure 4.7a) and no tolerance for angular misalignment (Figure 4.7b), U joints were selected. A single U-joint allows for angular misalignments, and a double U-joint assembly allows for both angular and axial misalignment. Double U-joints were constructed using two high-torque needle bearing U-joints connected with a small keyed 1045 shaft segment.

The double U-joints were too long to connect the sample and load roller shafts to the gear box where it was originally designed to be bolted down. Therefore, an extension plate was built onto the aluminum table base of the RSCF machine. The base of the gear box was also redesigned to incorporate elongated bolt holes. These holes allowed the gear box to be adjusted side-to-side. The main shaft no
longer had to be aligned with the gear box and the gear box could be quickly and easily aligned with the rest of the machine. The combination of the relatively higher tolerance for misalignment of the double U-joints and the adjustability of the gear box has made the RSCF machine more robust, quieter, and easier to set up. Figure 4.8 shows the installed configuration of the gearbox on the extension plate with both double U-joint assemblies.

A higher viscosity, high load bearing gear oil was used as the lubricant for the gear box, replacing the same Exxon oil used for the RSCF tests. This higher viscosity oil improved the lives of the gears in the gear box as well as significantly reduced noise associated with the gear box during RSCF testing.

4.6 Belt Tensioner

A constant force belt tensioner was installed in the RSCF machine as shown in Figure 4.9. The tensioner was purchased off-the-shelf, but the idler shaft had to be re-machined to match the bearing pulley. The shaft was annealed, turned down from 1” to 0.5” diameter using a lathe, and then quench and tempered to 40 HRC. The tensioner will apply the same force on the belt as the belt stretches over time.
Another issue associated with the early operation of the RSCF machine was that the computer which ran the LabView program used to control the RSCF machine was too slow. Data recording during normal testing would eventually slow the computer down leading to issues with control of the RSCF machine and causing the invalidation of tests. Also, the computer was not powerful enough to control the hydraulics and thus the load. The hydraulic load had to be controlled manually using the MTS® frame. The manual control was inexact and the voltage signal from the MTS frame would fluctuate leading to an inconsistent average load during RSCF testing.

A new computer was purchased and the LabView program was improved. The greatest improvement was the ability to control the applied load from the program and not from the MTS® frame. The load could be steadily increased as well using the program. The program also monitored the oil bath and oil feed temperatures. The program could detect if the oil pump shuts off leading to a temperature spike and would then shut down the RSCF machine before starved contact occurred. This added safeguard prevented the invalidation of several RSCF tests. Appendix A presents specifics on the use of the RSCF LabView program.
CHAPTER 5: COMPARISON OF RCF AND RSCF MACHINES

5.1 Introduction

The following chapter presents the comparative results of the fatigue testing performed on the rolling-sliding contact fatigue (RSCF) machine and the Federal-Mogul Ball-on-Rod rolling contact fatigue (FM RCF) machine and the subsequent analysis to attempt to correlate the fatigue performance of the two testing rigs. As mentioned in Chapter 4, the nominal Hertzian contact stress was 5.4 GPa (based on pure rolling conditions). Pure rolling was achieved in the RSCF machine by disengaging the gear box.

5.2 Sample Characterization

Both types of samples were machined from the same 4120 bar stock having the chemical composition given in Table 5.1 [44]. The samples were carburized to a target case depth of 1.0 mm (0.039”) by a local heat treating shop. Representative microstructures of the carburized case for both sample types are presented in Figure 5.1. The near surface cases consisted of martensite and retained austenite. There were no microstructural differences observed at corresponding depths. The case depths were measured using microhardness traverses. The results of the microhardness traverses for both sample geometries are shown in Figure 5.2. The surface roughness of both sample types and loading body types (bearing or load roller for FM RCF or RSCF machine, respectively) were measured using optical profilometry. A summary of the sample properties is given in Table 5.2.

<table>
<thead>
<tr>
<th>wt pct</th>
<th>C</th>
<th>Mn</th>
<th>Si</th>
<th>Ni</th>
<th>Cr</th>
<th>Mo</th>
<th>Al</th>
<th>N</th>
<th>S</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>4120</td>
<td>0.22</td>
<td>1.06</td>
<td>0.26</td>
<td>0.10</td>
<td>0.54</td>
<td>0.16</td>
<td>0.024</td>
<td>0.0094</td>
<td>0.032</td>
<td>0.014</td>
</tr>
</tbody>
</table>

Table 5.1 Chemical composition of SAE 4120 used for correlation testing [44].

Figure 5.1 Light optical micrographs of case microstructures of carburized 4120 (a) FM RCF sample and (b) RSCF sample. Etched with four percent nital.
Figure 5.2  Estimated hardness profiles (HRC) converted from HV (Equation [3.30]) (1000g load, 10 second dwell) of carburized 4120 samples used to estimate the case depth. (a) RSCF sample and (b) FM RCF sample.

Table 5.2  Measured properties of carburized 4120 RSCF and FM RCF samples used for correlation testing.

<table>
<thead>
<tr>
<th>Property</th>
<th>RSCF</th>
<th>FM RCF</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case Depth</td>
<td>0.4 mm</td>
<td>0.5 mm</td>
</tr>
<tr>
<td>Surface Hardness</td>
<td>63 HRC</td>
<td>65 HRC</td>
</tr>
<tr>
<td>Core Hardness</td>
<td>43 HRC</td>
<td>47 HRC</td>
</tr>
<tr>
<td>Surface Roughness</td>
<td>0.748 µm Ra</td>
<td>0.440 µm Ra</td>
</tr>
<tr>
<td>Loading Body Roughness</td>
<td>310 µm Ra</td>
<td>0.089 µm Ra</td>
</tr>
</tbody>
</table>

There were differences between the properties of the two types of samples that may have prevented a meaningful comparison to be made between the RSCF and FM RCF in terms of pure rolling conditions. The slight difference in case depth and core hardness was thought to be due to the smaller sample geometry (9.5 mm versus 25.4 mm diameter), mass, and higher cooling rate, of the FM RCF samples. The observed differences in sample surface roughness were due to machining differences. The ball bearings having a surface roughness of 0.089 µm Ra were manufactured differently than the RSCF 0.8” crown load rollers which explains the large difference in roughness. It was not feasible for the contracted machine shop to finish the crowned surface of the rollers to a similar roughness as the bearings.
5.3 Fatigue Testing Results

The results of the correlation testing are summarized in Table 5.3. The correlation tests showed a large difference in contact fatigue performance between the RSCF and FM RCF machine under pure rolling conditions at a nominal contact stress of 5.4 GPa. The RCF lives measured using the FM RCF machine were three orders of magnitude longer than the RSCF samples.

<table>
<thead>
<tr>
<th>Machine</th>
<th>FM RCF</th>
<th>RSCF</th>
</tr>
</thead>
<tbody>
<tr>
<td>Test Number</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Cycles to Failure (10^6)</td>
<td>37.5</td>
<td>11.6</td>
</tr>
</tbody>
</table>

5.4 Failure Analysis

Failure analysis of the samples was carried out to observe the pitting morphology developed by the two test machines and to possibly correlate the failure mode to the differences in fatigue lives. Profilometry was also conducted on the test wear tracks to differentiate the surface profiles produced during RCF testing.

5.4.1 Profilometry

The results of the profilometry scans are shown in Figure 5.3. Only one representative scan of each test sample is presented. There are obvious differences between the surface profiles developed for carburized 4120 (a) FM RCF and (b) RSCF samples showing profiles of the wear track at the onset and conclusion of RCF testing at 5.4 GPa.
each sample type. The wear track of the FM RCF samples was shallow, contained no indication of plastic deformation in the form of “lips” at the sides of the wear track (Figure 5.3b), and exhibited a double valley morphology which is typical of the FMRCF machine if the five contacting ball bearings are not perfectly aligned [44]. The wear track of the RSCF sample was much deeper, smoother, and exhibited large deformation lips at the sides of the wear track. These lips are characteristic of localized plastic flow around an indent that is deforming a surface, such as is observed in a hardness indent. Based on the profilometry results, it is likely that significant yielding occurred during the short RSCF tests leading to fatigue ratcheting, early ductility exhaustion, rapid cracking, and subsequent pitting.

5.4.2 Fractography

Fractographs were taken of the pits produced during RCF testing using a Nikon D70 digital camera and bellows system. Representative fractographs are shown in Figure 5.4 for each test type. The pits in the FM RCF tests (Figure 5.4a) appeared to have been produced from only a single pitting event where a single piece of metal spalled off. No cracking beside the pit was apparent. The pitting developed by the RSCF machine (Figure 5.4b) at 5.4 GPa exhibited evidence of significant fatigue damage: multiple spalling events led to the pits and a significant amount of cracking was readily observed in the wear track around the pit.

![Fractographs of pits produced during pure rolling tests at 5.4 GPa nominal Hertzian contact stress. (a) FM RCF test 1 pit developed after 37.5 million cycles. (b) RSCF test 1 pit developed after 0.012 million cycles. Rolling direction indicated by white arrows.](image)

5.5 Stress Analysis Results

A simplified Hertzian stress analysis was conducted to compare the estimated subsurface shear stress profile to the estimated shear yield strength of the carburized 4120 case. This analysis was used to investigate the probability that plastic flow would occur due to the applied 5.4 GPa contact pressure. The shear stress profiles were calculated according to the method described in the experimental procedure chapter. The shear yield strength was estimated according to Equation (5.1) [109].
\[ \tau_{ys} \approx \frac{3}{2} (HV) \]  
(5.1)

where HV is the Vickers hardness in kg/mm\(^2\) and \(\sigma_{ys}\) is the yield strength in MPa. The factor of three includes the conversion of kg/mm\(^2\) to MPa [109]. The yield strength is converted to shear yield strength by dividing by a factor of two. The results of the stress analysis are presented in Figure 5.5. Each plot in Figure 5.5a and Figure 5.5b includes two lines. One represents the estimates shear yield strength based on hardness measurements and the other is the estimated applied shear stress from contact.

In both sample geometries and loading conditions the calculated maximum shear stress profile exceeded the estimated shear yield strength over a range of depths below the surface. Comparing the amount of predicted yielding possible, a much larger volume of material was subject to stress that could result in plastic deformation in the RSCF samples. The greater amount of yielding is related to the sample and loading body geometries. The lips evident in Figure 5.3b are evidence for the yielding expected based on the results of Figure 5.5b. The maximum applied shear stress is the same for both the FM RCF and RSCF geometries. However, because the geometries (sample diameter, and load roller crown radius) are larger in the RSCF testing setup, the maximum shear stress profile is extended further into the subsurface. The maximum shear stresses are the same magnitude but occur at different depths.

It should be noted that the shear stress profiles were calculated based on a simplified sphere-on-sphere analysis and, therefore, are overestimates of the actual stress profiles and shear stress amplitudes. The overestimation may account for the FM RCF samples exhibiting relatively long contact fatigue lives even though the stress analysis suggested that local yielding should have occurred.

### 5.6 Summary

The correlation of the pure rolling results from the RSCF machine as compared to the FM RCF machine revealed that the pitting fatigue results for 4120 carburized to case depths less than 1.0 mm obtained by the RSCF machine at 5.4 GPa could not be correlated to those of the FM RCF machine. RSCF RCF lives three orders of magnitude shorter than those produced by the FM RCF setup were thought to be due to excessive cyclic yielding during the first few cycles in the RSCF machine. Evidence of yielding was observed in the appearance of lips around the wear track. Yielding was also expected based on the comparison of the estimated shear yield stress and strength profiles of the RSCF sample. The cyclic yielding or ratcheting was thought to have led to early exhaustion of the ductility and subsequent fracture. Increased case depths (2 mm or higher) were thought to be necessary to make a more accurate assessment. Subsequently, it was understood for future work using the RSCF machine, a deeper case depth was necessary to reduce the possibility of excessive yielding and the maximum contact that should be applied using the RSCF machine may be 3.2 GPa, as suggested by Davis [89].
Figure 5.5 Shear stress profile due to 5.4 GPa contact stress plotted with estimated shear yield strength of carburized 4120 (a) FM RSCF samples and (b) RSCF samples contacted with 12.7 mm (0.5\text{"") 52100 ball bearings and 23.32 mm (0.8\text{"") 52100 load rollers, respectively. The shaded areas represent locations where yielding is expected.
CHAPTER 6: RESULTS AND DISCUSSION

6.1 Materials Characterization

Four material conditions were considered in this work for evaluation of rolling-sliding contact fatigue (RSCF) resistance: vacuum carburized 4120 (4120V) and 4320 (4320V), and gas carburized 4120 (4120G) and 4320 (4320G). Both carburizing treatments were carried out at 1010°C (1850°F). The as-carburized material characteristics were investigated in an attempt to correlate differences in microstructure, presence of intergranular oxidation (IGO), depth of IGO, amount of retained austenite (RA), residual stress, case depth, carbon profiles, inclusion content, prior austenite grain size (PAGS), and hardness with RSCF resistance.

6.1.1 As Carburized Microstructure

Case/core microstructure transition micrographs are shown in Figure 6.1. The bulk of the as-carburized 4120 and 4320 case microstructure, observed using light optical microscopy (LOM), was found to be consistent with typical carburized microstructures reported in the literature [1, 44, 89]. There were some notable microstructure differences observed between the vacuum and gas carburized samples regarding the transition of the microstructure from the case to the core. The vacuum carburized samples exhibited a relatively abrupt transition from the case microstructure to the core. The transition from the case to core microstructure in the gas carburized samples was more gradual.

The case microstructures consisted of plate martensite and retained austenite, shown in Figure 6.2. The case microstructure of the vacuum carburized 4120 and 4320 also contained small amounts of bainite (Figure 6.3). Field emission scanning electron microscopy revealed a structure consistent with lower bainite (Figure 6.4). The presence of bainite was attributed to the less severe gas quench utilized for the vacuum carburizing which resulted in lower cooling rates. The core microstructures, presented in Figure 6.5, were comprised of Widmanstätten ferrite, bainite, and lath martensite. The vacuum carburized 4120 had the largest volume fraction of Widmanstätten ferrite and bainite. The vacuum carburized 4320 and gas carburized 4120 had increased fractions of martensite. The gas carburized 4320 core microstructure had the highest fraction of martensite. The relatively greater volume fraction of martensite in the gas carburized samples was most likely due to faster cooling rates achieved by oil quenching. Increased hardenability due to the nickel addition in the 4320 material presumably contributed to developing the higher martensite fraction, compared to 4120, for both heat treatments. (The ideal diameters of the 4120 and 4320 were estimated to be 2.0 and 2.4 inches, respectively, based on calculations performed according to ASTM A255 Table 6 [110] for an ASTM grain size of 7.)
Figure 6.1 Case and core LOM images of carburized 4120 and 4320 RSCF samples at 100X original magnification. (a) Vacuum carburized 4120, (b) gas carburized 4120, (c) vacuum carburized 4320, and (d) gas carburized 4320. Transverse section view. Picral etch.
Figure 6.2  Light optical micrographs of case microstructure of vacuum carburized (a) 4120 and (b) 4320 and gas carburized (c) 4120 and (d) 4320. Taken depth of ~100 µm. Transverse section view. Picral etch.

Figure 6.3  Light optical micrographs of case microstructure of vacuum carburized (a) 4120 and (b) 4320. The darker etching features are bainite. Taken at depth of ~100 µm. Transverse section view. Picral etch.
Figure 6.4  Representative secondary electron micrograph of lower bainite observed in case of vacuum carburized 4320. Taken depth of ~100 µm. Transverse section view. Picral etch.

Figure 6.5  Light optical micrographs of core microstructure of vacuum carburized (a) 4120 and (b) 4320 and gas carburized (c) 4120 and (d) 4320. Transverse section view of center of carburized bar sample. Picral etch.
6.1.2 Inclusion Analysis

Inclusion analysis for the 4120 and 4320 steels was performed by The Timken Company. ASTM E45-13 inclusion analysis [102] based on the worst field method for both steels was performed and the results are shown in Table 6.1. An A type inclusion refers to sulfide inclusions. B type refers to globular oxide inclusions, C type inclusions are silicates, and D type refer to alumina inclusions. Overall the 4120 steel had a slightly more severe sulfide inclusion content and the 4320 had a more severe oxide/alumina content. The severity parameter listed has a minimum value of 0.5 and a maximum value of 5.0. A value of 0.0 indicates that the inclusion type was not observed. A higher severity parameter for a given inclusion type would be expected to negatively impact contact fatigue resistance, although the observed differences in inclusion severity parameter between the 4120 and 4320 alloys was not thought to be large enough to impact RSCF results.

Table 6.1  ASTM E4-135 inclusion ratings for 4120 and 4320 steel performed by The Timken Company.

<table>
<thead>
<tr>
<th>Steel</th>
<th>A-thin</th>
<th>A-heavy</th>
<th>B-thin</th>
<th>B-heavy</th>
<th>C-thin</th>
<th>C-heavy</th>
<th>D-thin</th>
<th>D-heavy</th>
</tr>
</thead>
<tbody>
<tr>
<td>4120</td>
<td>2.2</td>
<td>0.9</td>
<td>0.5</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>1.0</td>
<td>0.6</td>
</tr>
<tr>
<td>4320</td>
<td>1.8</td>
<td>0.8</td>
<td>0.8</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>1.0</td>
<td>0.8</td>
</tr>
</tbody>
</table>

6.1.3 Carbon Profile

The results of the carbon analysis are presented in Figure 6.6. The greater surface hardness of the vacuum carburized specimens was consistent with their greater carbon concentrations. The target surface carbon content was 0.9 weight percent for both heat treatments. The surface carbon content of the vacuum carburized 4120 was higher than the gas carburized 4120 (0.87 versus 0.75 weight percent, respectively). The surface carbon content of the vacuum carburized 4320 was also higher than the gas carburized 4320 (0.81 versus 0.70 weight percent, respectively). The vacuum carburized samples had greater carbon contents (about 0.1 to 0.2 weight percent more) than the gas carburized samples for all depths measured in the analysis.

6.1.4 Hardness and Case Depth

Effective case depth measurements for the four alloy/heat treatment conditions revealed increased case depths in the gas carburized samples, based on the hardness profiles shown in Figure 6.7. Figure 6.7a shows the hardness profiles of the carburized 4120 steels and Figure 6.7b shows the hardness profiles of the carburized 4320 steels. The error bars in Figure 6.7 represent the standard error. The greater surface hardness of the vacuum carburized specimens is consistent with their greater carbon concentrations. The 4120 and 4320 gas carburized samples had an effective case depth of 1.50 mm (0.059”). The vacuum
carburized 4120 and 4320 had effective case depths of 1.40 and 1.26 mm (0.055” and 0.050”, respectively). The difference in case depths between the vacuum carburized conditions was thought to be due to either the increased load (number/weight of samples) in the vacuum carburizing furnace with the same carburizing parameters [88] (twelve 4120 samples versus twenty two 4320 samples were carburized in separate batches), or possibly differences in chemistry. By inspection of Figure 6.1 and Figure 6.7, the case depth/relatively steep hardness decrease measured for the vacuum carburized samples corresponds well with the abrupt change in the case to core microstructure. The increased core hardness of the gas carburized samples also increased the effective case depth by decreasing the gradient of the transition between the case and core hardness.
Figure 6.7 Microhardness profiles, converted from HV (1 kg load, 10 sec dwell) to HRC, of vacuum and gas carburized 4120 and 4320 RSCF samples. (a) 4120 and (b) 4320. Case depth estimated at 50 HRC.

The core hardness of each condition corresponds to the observed microstructure. The 4120V having the lowest core hardness also had the lowest volume fraction of martensite, the 4320V and 4120G had higher core hardesses and more martensite, and the 4320G, exhibiting the hardest core, contained a core consisting primarily of martensite.

6.1.5 Prior Austenite Grain Size

The PAGS was observed using LOM after etching with saturated aqueous picric acid and the results are summarized in Table 6.2. Representative LOM images of the etched prior austenite grain (PAG) boundaries are shown in Figure 6.8. Quantitative analysis revealed that the grain sizes for the four conditions varied between ASTM 8.4 and 9.0, values which were interpreted to be essentially equivalent.
It should be noted that the grain sizes measured were not located in the near surface case of the carburized samples. The near surface PAG boundaries of the case were not able to be etched for analysis. Grains observed deeper into the case near the case/core transition were used for measurement. The grain sizes measured were confirmed to be accurate based on fractography and intergranular oxide surrounded grains observed through chordal sectioning in the gas carburized samples.

<table>
<thead>
<tr>
<th>Condition</th>
<th>Average Grain Diameter</th>
<th>ASTM Grain Size Number</th>
</tr>
</thead>
<tbody>
<tr>
<td>4120V</td>
<td>22.1 ± 0.3 µm</td>
<td>8.4</td>
</tr>
<tr>
<td>4320V</td>
<td>20.7 ± 0.3 µm</td>
<td>8.6</td>
</tr>
<tr>
<td>4120G</td>
<td>19.0 ± 0.3 µm</td>
<td>8.8</td>
</tr>
<tr>
<td>4320G</td>
<td>17.7 ± 0.3 µm</td>
<td>9.0</td>
</tr>
</tbody>
</table>

Figure 6.8 Light optical micrographs of prior austenite grain structure in carburized RSCF samples for grain size measurement. Vacuum carburized (a) 4120 and (b) 4320; and gas carburized (c) 4120 and (d) 4320. Black spots are etch pits. Transverse section view. Saturated, aqueous picric acid etch.
6.1.6 Intergranular Oxidation

IGO of the carburized specimens was observed in the gas carburized samples using scanning electron microscopy (SEM) backscattered electron imaging. Representative images of the extent and morphology of IGO are shown in Figure 6.9. The average IGO depth of the vacuum carburized samples was taken to be 0.0 µm because IGO could not be resolved at the surface using SEM. The average, characteristic IGO depths of the gas carburized 4120 and 4320 were 16.3 and 15.6 µm, respectively. The standard deviations of the IGO measurements were 1.0 and 0.6 µm, respectively. There did not appear to be a statistically significant difference in the extent of IGO penetration between the gas carburized 4120 and 4320. The morphology of the oxides observed in the 4120 and 4320 did not appear to exhibit obvious differences. The notable difference in the surface profiles between the vacuum carburized samples (Figure 6.9a and Figure 6.9b) and gas carburized samples (Figure 6.9c and d) is due to vacuum grooving in the vacuum carburized samples.

![Figure 6.9](image)

Figure 6.9 Representative backscatter electron micrographs of surface intergranular oxidation (or absence of intergranular oxidation) of vacuum and gas carburized RSCF samples. Vacuum carburized (a) 4120 and (b) 4320. Gas carburized (c) 4120 and (d) 4320. 500X original magnification. Transverse section view. As-polished.
6.1.7 Near-Surface Non-Martensitic Transformation Products

A notable volume fraction of non-martensitic transformation products (NMTP) was observed at the surface of the vacuum carburized samples. LOM images of the NMTP are shown in Figure 6.10. The light etching features are martensite and retained austenite. The dark etching features are NMTP. No difference in the morphology or extent of the NMTP was observed between the vacuum carburized 4120 and 4320. It was presumed that the NMTP in the vacuum carburized samples was due to the lower cooling rate from gas quenching (compared to oil quenching). Higher resolution microscopy of the NMTP confirmed the presence of fine pearlite in addition to bainite as shown in Figure 6.11.

![Figure 6.10](image)

**Figure 6.10** Light optical micrographs of non-martensitic transformation products (dark etching features) observed at the near surface using chordal section of vacuum carburized (a) 4120 and (b) 4320. Picral etch.

![Figure 6.11](image)

**Figure 6.11** Representative secondary electron micrographs of non-martensitic transformation products observed near the surface using chordal sectioning of vacuum carburized 4120 (similar structures observed in 4320). (a) 2000X original magnification. (b) 10,000X original magnification showing fine pearlite. Picral etch.
Investigations of the chordal sections of the gas carburized 4120 and 4320 also revealed some NMTP (Figure 6.12) associated with IGO. The lower resolution (1000X magnification) LOM investigation of the IGO NMTP revealed differences in the amount of NMTP associated with IGO between the gas carburized 4120 and 4320. The 4120G exhibited more NMTP than the 4320G around IGO (qualitatively comparing the amount of the dark etching features in Figure 6.12a versus Figure 6.12b). Manganese was shown to be a potent IGO forming element by Chatterjee-Fischer [12]. By forming IGO, the local concentration of manganese was lowered at the surface around the IGO and the surface hardenability was decreased. Nickel is not oxidized during gas carburizing [12] and also increases hardenability. Therefore, it was interpreted that the nickel addition helped to inhibit NMTP formation in the gas carburized 4320, by maintaining some surface hardenability in the presence of local manganese oxidation. SEM revealed the microstructure of the NMTP to be bainitic and possibly pearlitic, shown in Figure 6.13. A higher volume fraction of NMTP was observed around IGO located nearer to the carburized surface as compared to IGO located further from the surface near the limit of IGO penetration in the gas carburized case.

![Figure 6.12](image)

(a) 10 μm (b) 10 μm

Figure 6.12 Light optical micrographs of non-martensitic transformation products (dark etching features) located adjacent to intergranular oxides in carburized RSCF samples viewed using chordal section. Gas carburized (a) 4120 and (b) 4320. Picral etch.

Comparing the vacuum versus gas carburized heat treatments (Figure 6.10 versus Figure 6.12), the vacuum carburized samples exhibited more surface NMTP than the gas carburized samples. The increased fraction of NMTP was thought to be due to the lower cooling rate developed for the vacuum carburized samples. The NMTP in the gas carburized samples was only associated with IGO. Pearlite was found in the vacuum carburized specimens, and possibly in the gas carburized 4120.
Figure 6.13 Secondary electron micrograph of non-martensitic transformation products (bainite and possibly pearlite) observed around surface oxides (globular features) in gas carburized 4120. (a) Higher volume fraction of bainite/pearlite near surface and (b) relatively lower volume fraction of bainite near maximum depth of oxide penetration. Picral etch.

6.1.8 Residual Stress

Near-surface residual stress measurements (up to 0.64 mm or 0.025”’) revealed non-typical residual stress profiles for the vacuum carburized 4120 and 4320 as shown in Figure 6.14; typically, maximum compressive residual stresses are reported at the surface and decrease with depth until they become tensile [5, 6]. The vacuum carburized residual stress profiles are considered non-typical because the compressive residual stresses appeared to decrease in magnitude near to the surface; also, the residual stress measurements were not made deep enough to observe the expected decrease in compressive residual stresses until they transition to becoming tensile (positive residual stress). Similar behavior to the vacuum carburized 4120 and 4320 has also been reported in work done by Bensely et al. [111], although the indicated study was conducted on gas carburized EN 353 steel carburized at a lower carbon potential of 0.75. The magnitudes of the surface residual stresses of the vacuum carburized samples were similar (about -200 MPa) to those measured by Bykowski [44]. Other than the near-surface behavior, the residual stress measurements were similar in magnitude to those measured in a previous study of vacuum carburized steels at depths of 0.2 mm and more [112]. It is likely that the near-surface NMTP, presumably developed due to low cooling rates in the vacuum carburized samples, contributed to a decrease in the near-surface compressive residual stresses. A similar effect of NMTP on residual stress distributions in carburized steel has been shown previously by Naito et al. [113].

The gas carburized samples were also shown to have compressive residual stresses, although a tensile residual stress of 61 MPa was measured at the surface of the gas carburized 4120. The gas carburized 4120 exhibited significant amounts of NMTP associated with surface IGO, although not as much as the vacuum carburized samples. The NMTP may have contributed to the tensile residual stress at
the surface in the 4120 as compared to the gas carburized 4320 which had the greatest compressive
residual stress at the surface (about -450 MPa). Recall that the 4320 contained insignificant amounts of
NMTP associated with IGO as compared to the gas carburized 4120 which is thought to be the reason for
the higher compressive residual stress.

Figure 6.14 Residual Stress profiles of carburized RSCF samples measured using XRD. Vacuum
carburized (a) 4120 and (b) 4320; gas carburized (c) 4120 and (d) 4320.

6.1.9 Retained Austenite

The RA profiles of the vacuum and gas carburized 4120 and 4320 are shown in Figure 6.15. Figure 6.15 shows that amount of RA is highest just below the surface and decreases with depth. The behavior of the RA as a function of depth was similar for the four material/heat treat conditions. The percent RA was maximal just below the surface and decreased with depth, except for the vacuum
carburized 4320. The vacuum carburized samples had higher amounts of RA overall, versus depth than the gas carburized samples. This is most likely due to the higher carbon content of the vacuum carburized samples.

![Graphs showing retained austenite profiles of carburized RSCF samples measured using XRD.](image)

**Figure 6.15** Retained austenite profiles of carburized RSCF samples measured using XRD. Vacuum carburized (a) 4120 and (b) 4320; and gas carburized (c) 4120 and (d) 4320.

### 6.1.10 Summary

A brief summary of the material properties and characteristics of the vacuum and gas carburized 4120 and 4320 is presented in Table 6.3. The gas carburized samples had higher case depths possibly due to their increased core hardness. The case hardnasses of the four conditions were relatively similar. The average PAGS were also similar and were not thought to vary enough to contribute to substantial differences in contact fatigue properties. Only the gas carburized samples contained IGO. NMTP was
associated with the IGO, especially in the gas carburized 4120. More surface NMTP was observed in the vacuum carburized samples. It is postulated that the reduced cooling rate in the vacuum carburizing process was responsible. The NMTP apparently lowered the magnitude of the near surface compressive residual stresses due to carburizing. The vacuum carburized samples had higher amounts of RA, presumably due to higher carbon content.

Table 6.3 Summary of material properties of vacuum and gas carburized 4320 and 4120.

<table>
<thead>
<tr>
<th>Material</th>
<th>4120</th>
<th>4320</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heat Treatment</td>
<td>Vacuum Carburized</td>
<td>Gas Carburized</td>
</tr>
<tr>
<td>Case Depth (mm)</td>
<td>1.40</td>
<td>1.50</td>
</tr>
<tr>
<td>Surface Carbon (weight percent)</td>
<td>0.87</td>
<td>0.75</td>
</tr>
<tr>
<td>Surface Hardness (HRC)</td>
<td>63.5</td>
<td>62.1</td>
</tr>
<tr>
<td>Core Hardness (HRC)</td>
<td>23.3</td>
<td>40.1</td>
</tr>
<tr>
<td>Average PAGS (µm)</td>
<td>22.1 ± 0.3</td>
<td>19.0 ± 0.3</td>
</tr>
<tr>
<td>IGO depth (µm)</td>
<td>0.0</td>
<td>16.3</td>
</tr>
<tr>
<td>Surface Residual Stress (MPa)</td>
<td>-182 ± 46</td>
<td>+61 ± 8</td>
</tr>
<tr>
<td>Surface RA (%)</td>
<td>28.1</td>
<td>11.6</td>
</tr>
</tbody>
</table>

6.2 Rolling-Sliding Contact Fatigue Life

The RSCF life data are presented in Table 6.4 and graphically in Figure 6.16. Six tests were performed for the vacuum carburized 4120. Three tests were performed for the gas carburized 4120 condition. Five tests were performed for the vacuum carburized 4320 condition. One RSCF test was conducted for the gas carburized 4320 condition. The original goal of the project was to conduct up to six RSCF tests per condition. Lack of usable samples (due to distortion discussed in Chapter 4) for the gas carburized conditions prevented the full test matrix from being completed.

There were apparent differences in the average fatigue lives of the four conditions. The average fatigue life of the vacuum carburized 4120 was 0.877 million cycles. The average fatigue life of the gas carburized 4120 was 1.770 million cycles. The average fatigue life of the vacuum carburized 4320 was 1.314 million cycles. The fatigue life of the gas carburized 4320 test was 3.708 million cycles. While more test replicates would have been helpful to improve the statistical quality of the data, for the heat
treated parameters and aggressive RSCF testing conditions employed in this work, the gas carburized samples appear to be more resistant to pitting than the vacuum carburized samples. For both heat treatment conditions the 4320 alloy also showed possible increased pitting resistance over the 4120, in terms of the maximum fatigue life measured. The 4120 alloy, for both heat treat conditions, exhibited more consistent lives, as illustrated by the error bars in Figure 6.16, than the 4320 alloy (based on the 4320V, since the 4320G involved only a single test).

Table 6.4 Summary of RSCF lives of vacuum and gas carburized 4120 and 4320.

<table>
<thead>
<tr>
<th>Material</th>
<th>Heat Treatment</th>
<th>Test Number</th>
<th>RSCF Lives (10^6 cycles)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4120</td>
<td>Vacuum Carburized</td>
<td>1</td>
<td>0.899</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
<td>0.750</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3</td>
<td>0.784</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4</td>
<td>0.962</td>
</tr>
<tr>
<td></td>
<td></td>
<td>5</td>
<td>0.966</td>
</tr>
<tr>
<td></td>
<td></td>
<td>6</td>
<td>0.900</td>
</tr>
<tr>
<td></td>
<td>Gas Carburized</td>
<td>7</td>
<td>1.960</td>
</tr>
<tr>
<td></td>
<td></td>
<td>8</td>
<td>1.501</td>
</tr>
<tr>
<td></td>
<td></td>
<td>9</td>
<td>1.849</td>
</tr>
<tr>
<td>4320</td>
<td>Vacuum Carburized</td>
<td>10</td>
<td>0.696</td>
</tr>
<tr>
<td></td>
<td></td>
<td>11</td>
<td>2.272</td>
</tr>
<tr>
<td></td>
<td></td>
<td>12</td>
<td>0.463</td>
</tr>
<tr>
<td></td>
<td></td>
<td>13</td>
<td>1.639</td>
</tr>
<tr>
<td></td>
<td></td>
<td>14</td>
<td>1.500</td>
</tr>
<tr>
<td></td>
<td>Gas Carburized</td>
<td>15</td>
<td>3.708</td>
</tr>
</tbody>
</table>

Figure 6.16 Average RSCF lives of vacuum and gas carburized 4120 and 4320 obtained at 3.2 GPa nominal Hertzian contact stress, 100°C, and -20 percent slide ratio. Error bars represent the range observed in life data.
6.3 Wear Track Analysis of Pitted Samples

The wear track profiles from each RSCF test are presented in Figure 6.17 to Figure 6.20. In each figure two profiles are shown, the profile prior to testing (onset) and the profile after testing (conclusion). The vacuum and gas carburized 4120 specimens displayed a “tighter” range of pitting lives; the 4120 wear tracks were also similar to one another, in terms of width, depth, and curvature. An exception was 4120V test 2 (Figure 6.17b) which showed an irregular wear track; it was interpreted that the relatively more “tortuous” wear track was created by artificial damage possibly caused by spalled metal entering the contact zone leading to wear and denting of the wear track, thereby producing a wear profile not representative of the wear track morphology at the time of pitting. The wear track profiles of the vacuum carburized 4320 samples shown in Figure 6.19 were more variable, that is the wear track widths, depths, and curvatures of each test was different than the others in the 4320V condition. The appearance of the wear tracks of the 4320 samples seemed to relate to the pitting lives which were more variable for 4320V than for the 4120V conditions. It should also be noted that the tests with the longest fatigue lives (4320V test 11 and 4320G test 15) had the shallowest wear depth (7 to 10 µm deep). The test with the shortest fatigue life (4320V test 12) had one of the deepest wear tracks as well as a thinner wear profile, possibly indicating more localized wear. The observed correspondence between wear track morphology, especially depth, and pitting lives (similar wear track profiles of conditions with less variable fatigue lives, and vice versa) was consistent with the literature. Krantz et al. [114] and Wagar [93] also showed an increase in pitting lives associated with decreased wear during RSCF testing; however, no explanations were presented for the behavior.

It is hypothesized in this work that the ability of the wear track to shake-down and reach/maintain a steady state run-in condition may have been driving the observed correlation between wear and pitting behavior. Adachi et al. [73] showed that carburized gear steels had the largest resistance to pitting from RSCF if they were able to achieve a steady state run-in condition during operation. Shakedown is defined as the process where a loaded contact body which deforms plastically, or by wear initially during cyclic loading, reaches a steady state in which the material response to additional loading cycles is perfectly elastic (run-in) [69]. In the case of the RSCF testing in this study, shakedown may have been related both to wear and plastic deformation of the surface until the wear track profile reached a steady state condition. In this steady state/run-in condition, it is hypothesized, in this work, that the rate of accumulation of deformation, fatigue damage (crack nucleation and propagation), and wear was lowest leading to longer pitting lives. If the run-in condition was disrupted, through additional localized wear, it is postulated that further deformation/wear of the “disrupted” wear track would then be more likely to occur to reach a new run-in condition. The additional deformation and wear may have caused more damage and increased the probability of fatigue cracking leading to pitting.
Figure 6.17  Surface profile at onset and conclusion, as shown in (a), of RSCF testing of vacuum carburized 4120 tests 1 through 6. Measured using optical profilometry, tilt term filtered from analysis.
Figure 6.18 Surface profile at onset and conclusion, as shown in (a), of RSCF testing gas carburized 4120 tests 7 through 9. Measured using optical profilometry, tilt term filtered from analysis.

The hypothesized explanation did not consider residual stresses which may be altered by RSCF, and was not supported by microstructural investigation of deformation. An analysis of residual stress, as well as investigation of dislocation density changes to confirm the extent of deformation beneath the wear track would be beneficial to improve the strength of the proposed explanation. Also, the strength of the hypothesis would have been improved with more test replicates. Section 6.5.1 provides additional analysis of wear and run-in during the initial stages of the RSCF wear track life.
Figure 6.19 Surface profile at onset and conclusion, as shown in (a), of RSCF testing of vacuum carburized 4320 tests 10 through 14. Measured using optical profilometry, tilt term filtered from analysis.
6.4 Failure Analysis

This section presents the results of the investigation of the cracking and failure associated with macropit formation during RSCF testing to failure. Evolution of the surface and subsurface damage prior to the failure is discussed in Section 6.5 below.

6.4.1 Pit Morphology

The macropits produced during RSCF testing were investigated to observe fracture initiation sites and modes of propagation. For all macropits produced (representative pits are shown in Figure 6.21) the morphology was consistent with point-surface origin type pitting. Each pit had an arrowhead front which pointed in the rolling direction. The pit front was oriented at a shallow angle to the rolling surface. The rear of each pit was less pointed and had steep walls. Additional cracking was always observed behind the pit indicating further subsurface crack propagation. There were no observable trends in pit depth or size as they related to RSCF life consistent with the literature [115].

6.4.2 Initiation

The tips of each macropit were examined at higher magnification to determine the initiation site and mechanism. No evidence of surface defects such as scratches, dents, or machining marks was present that would have contributed to the point surface origin morphology of the pits. Micropitting and microcracking were always observed at the tip of each RSCF pit. Representative micrographs of these features are provided in Figure 6.22. Figure 6.22 shows the micropitting and microcracking at the pit tips as indicated by the white arrows. In some cases the cracking features of the macropit tips may have originated directly from the micropitting and microcracks. Therefore, the initiation site for macropitting during RSCF testing for all conditions appeared to be micropitting and surface microcracks.

Figure 6.20 Surface profile at onset and conclusion of RSCF testing of gas carburized 4320 test 15. Measured using optical profilometry, tilt term filtered from analysis.
6.4.3 RSCF Fracture Appearance

Typical cracking behavior leading to the macropitting observed in this study is illustrated in Figure 6.23 which shows the base of the macropits (a) and the transverse sections of the pits (b). The fracture features at the base of the pits were smeared due to the crack faces being pressed and perhaps, rubbed together during each contact cycle. No obvious intergranular or intragranular fracture modes were apparent at the base of the pits. In fourteen of the fifteen RSCF tests (excluding 4320G test 15) the fracture at the base of the pits had a somewhat step-like morphology due to multiple subsurface cracks branching out during propagation. Subsurface cracks which propagated parallel to the contact surface were also typically observed. These cracks led to the observed, relatively flat pit bases in most RSCF pits (see Figure 6.23b). The pit produced during gas carburized 4320 test 15 (Figure 6.24) had much different
fracture features than the other RSCF tests. The base of the pit was very smooth (and smeared) with little indication of significant crack branching during propagation. The angle of the fracture relative to the surface was more consistent, possibly indicated less crack branching. The difference in behavior between the cracking leading to pitting in the gas carburized 4320 test 15 (3.7 million cycles) and the other RSCF tests (0.4 to 2.3 million cycles) perhaps indicated that the gas carburized 4320 was more resistant to cracking and consequently exhibited longer pitting lives during RSCF.
Figure 6.23  Representative secondary electron SEM micrographs of typical fracture appearance from 4120V test 9 at (a) the base of RSCF macropits and (b) transverse cross section of typical RSCF pit. The typical macropits exhibited extensive subsurface cracking and crack branching. Cracking did not appear to propagate at any consistent angle. Rolling direction indicated by arrows.

In contrast to the base of the pits, the pit wall features were more consistent (flatter and exhibited less steps). The pit walls near the front of each pit were smooth as shown in Figure 6.25. Because the pit walls were smooth it was concluded that they were developed well before the final failure (macropitting) event as cracks propagated perpendicular to the rolling direction up to, or from, the wear track surface. The faces of these cracks were pressed together and fracture features were smeared. The fracture features associated with pit walls present near the back and at the rear of the pits were better preserved (perhaps because they formed at the end of fatigue testing and there were fewer stress cycles applied to press the faces together). Intergranular fracture was typically observed on the pit walls near the rear of the pits for vacuum and gas carburized 4120 and 4320. Representative micrographs of intergranular fracture are shown in Figure 6.26. The observation of intergranular fracture was consistent with the literature [115].
Figure 6.24 Secondary electron SEM micrographs of non-typical cracking observed in gas carburized 4320 test 15. The base (a) of the macropit was relatively smooth and did not indicate substantial crack branching. The transverse cross section (b) of the pit confirmed that the primary crack associated with the pit did not branch into multiple cracks until the relative end of the RSCF test. Rolling direction indicated by white arrows.

Figure 6.25 Representative secondary electron SEM micrograph of a typical RSCF pit smooth, side “wall” (lighter portion in center of image). Image taken from location shown in (b) pit produced during 4320V test 11. Rolling direction up.
Intergranular fracture was observed in the gas carburized 4120 samples away from pit walls. The intergranular fracture features were not observed at the base of the full pit but off to the sides. This intergranular fracture was thought to occur rapidly, as a consequence of the macropit spalling off, at the end of the RSCF test. The well preserved fracture features in Figure 6.27 support the theory. The presence of intergranular fracture features was observed in the other two gas carburized 4120 tests. It was not
apparent if or how this intergranular fracture affected the formation of the macropit. It appeared that the gas carburized 4120 had a lower resistance to intergranular fracture. Intergranular oxidation may have played a role in the intergranular fracture.

6.4.4 Effect of IGO on Pitting

The presence of IGO was shown to be one of the largest differences in the material characteristics between the heat treatment conditions. SEM was used to observe IGO in the wear track transverse cross sections after RSCF testing in the as polished condition. A representative image from gas carburized 4120 test 7 is shown in Figure 6.30. IGO was still present up to about 8 to 10 µm below the wear track surface. The wear track depth of 4120G test 7, shown in Figure 6.29, was measured to be about 15 to 17 µm. The characteristic IGO depth of the gas carburized 4120 was 16.3 µm. If abrasive wear was the only mechanism involved in the wear track creation, then the majority of the surface material containing the IGO would be expected to have been removed (perhaps ~1 µm of IGO would remain). Therefore, deformation, which does not remove material, in addition to wear is hypothesized to contribute to the wear track creation.

![Figure 6.30 Representative backscatter electron SEM image of IGO still present beneath the wear track from gas carburized 4120 test 7. Transverse section view. Rolling direction indicated by arrow. As-polished.](image)

Because IGO is still present at the time of pit formation, pitting resistance in the gas carburized specimens may be decreased. However, the effect of IGO on the pitting resistance of the gas carburized samples was not conclusively shown. No grain pullout around IGO was observed in contrast to observations by Bykowski [44]. The abnormal, intergranular fracture of the gas carburized 4120 specimens mentioned previously (Figure 6.28) may have been influenced by the IGO. No clear correspondence between IGO and pitting was observed in the gas carburized 4320 specimen. More test replicates may be necessary to make a conclusive connection between IGO and RSCF resistance.

6.4.5 Butterflies

The origin of macropitting was concluded to be micropitting and microcracking in the near-surface case. The microcracking was often associated with butterfly features observed according to the
sectioning schematic presented in Figure 6.31. The butterflies were, therefore, thought to possibly contribute to the microcracking leading to micropitting. Referencing the literature, butterflies are microstructural features which develop around non-metallic inclusions and consist of white etching “wings” and microcracks which originated at the inclusion [115]. An investigation of the formation of butterflies and their associating with microcracking is presented in Section 6.5.2.

Butterflies were observed below the wear tracks of all RSCF tests. Examples of representative butterflies observed for each condition are shown in Figure 6.32. A high magnification electron micrograph clearly showing the wing/microcrack structure is presented in Figure 6.33. The butterfly wings and cracks were typically oriented parallel to the rolling direction (±10°). The butterflies were usually found around globular oxide inclusions. In some very rare cases, butterflies were found originating from sulfide inclusions.

There were differences in the morphologies of the butterflies between the four conditions, especially between the vacuum carburized samples and the gas carburized samples. The butterflies in the vacuum carburized 4120 and 4320 were larger in terms of wing size and length. They were also commonly associated with bainite. The dark etching features around the butterflies in Figure 6.32a and Figure 6.32b are bainite. The bainite may have contributed to butterfly formation and to the increased wing sizes observed. The mechanism associated with this contribution was unclear, although bainite is likely less resistant to plastic deformation than martensite, so may be more likely to nucleate fatigue cracks. The butterfly features observed in the gas carburized 4120 and 4320 were typically much smaller (length and width of wings), relative to the vacuum carburized conditions.
Figure 6.32 Light optical micrographs of butterflies formed during RSCF testing. (a) 4120V test 5, (b) 4320V test 10, (c) 4120G test 9, (d) 4320G test 15. Rolling direction and orientation of surface depicted by black arrows. Transverse section view. Picral etch.

Figure 6.33 Field emission secondary electron SEM image of butterflies formed during vacuum carburized 4320 test 14 showing cracks associated with butterfly wings. Rolling direction shown by black arrow. Transverse section view. Picral etch.
The probability of butterfly formation around non-metallic inclusions was calculated using the simplistic probability analysis presented in the experimental procedure chapter (the probability of butterfly formation was calculated by dividing the number total of butterflies formed around non-metallic inclusions by the total number of non-metallic inclusions, observed at 200X magnification using LOM). Sulfide inclusions were excluded from the analysis as butterfly formation around sulfides was very rare. The probabilities of butterfly formation rounded to the nearest 0.05 are presented in Table 6.5. The probabilities of each condition were plotted against the corresponding average RSCF lives in Figure 6.34. The RSCF resistance of the material condition increases as the probability of butterfly formation decreases, suggesting a possible relationship between pitting failure and butterfly formation.

<table>
<thead>
<tr>
<th>Condition</th>
<th>Probability of Butterfly Formation</th>
</tr>
</thead>
<tbody>
<tr>
<td>4120V</td>
<td>0.60</td>
</tr>
<tr>
<td>4320V</td>
<td>0.30</td>
</tr>
<tr>
<td>4120G</td>
<td>0.50</td>
</tr>
<tr>
<td>4320G</td>
<td>0.05</td>
</tr>
</tbody>
</table>

Figure 6.34 Average RSCF life versus probability of butterfly formation around non-metallic inclusion of vacuum and gas carburized 4120 and 4320 tested at 3.2 GPa, 100°C, and -20 percent slide ratio.

6.4.6 White Etching Cracks

Microstructural changes associated with contact fatigue similar to butterflies are white etching cracks (WEC). Butterflies are always associated with a non-metallic inclusion, whereas WEC were shown
by Evans [30] to be white etching features associated with subsurface cracking not necessarily originating from a non-metallic inclusion. WEC were observed in the vacuum carburized 4120 and 4320 and gas carburized 4120 (WEC were not observed in the gas carburized 4320). There were two different types of WEC present beneath the wear tracks after RSCF testing. The first type were near-surface WEC (shown in Figure 6.35a and Figure 6.35b). The WEC near the surface were sometimes, but not always associated with butterflies and were typically concave away from the surface. The near-surface WEC often had cracks extending to the surface and could therefore lead to micropitting. Also, the near surface WEC usually exhibited the white etching feature above the crack. This may explain why the white etching features were not observed at the base of micropits as the spalled-off material may have contained the WEC. Analysis of spalled material was not able to be conducted so this hypothesis cannot be proved. The second type of WEC was subsurface WEC and butterfly networks observed only in the 4120V

Figure 6.35  Representative light optical micrographs of white etching cracks observed after RSCF testing of vacuum and gas carburized 4120 and 4320. Near-surface white etching cracks from (a) 4320V test 14 and (b) 4120V test 3. Subsurface crack networks observed in vacuum carburized 4120 (c) test 3 and (d) test 6. Rolling direction and orientation of surface indicated by arrows. Transverse section view. Picral etch.
The crack networks appeared to originate from cracks linking butterflies together. Bainite also appeared to be associated with these crack networks in the 4120V.

Three observations were made regarding WEC that were thought to provide some insight into a possible relationship between the white etching features and the microcracks. Microcracking extending from WEC was observed to be present beyond any associated white etching features. The white etching feature associated with WEC was never observed in the absence of a microcrack. Also, the thickness of the WEC appeared to decrease near the apparent tip of the microcracks. It was postulated that the microcrack appears before, and is necessary for, the formation of the white etching feature. Once the crack has formed, the white etching feature begins to develop and both may grow somewhat cooperatively with the white etching feature slightly lagging behind the crack tip. These observations and white etching feature/microcrack relationships have been presented in the literature [30]. It should be noted that the early stages of the subsurface microcracking leading to the WEC were not observed in this study, or in the literature, in the specimens carried out to pitting failure. Therefore it is difficult to make a conclusive argument for the true WEC formation mechanism.

6.4.7 Characterization of Butterfly Microstructure

The microstructures of selected butterflies were analyzed using electron backscatter diffraction (EBSD) and transmission electron microscopy (TEM). EBSD was performed on butterflies observed in transverse sections of the wear track from 4320V test 14 in the as polished condition. TEM samples were prepared using focused ion beam (FIB) milling. This work was done in conjunction with an NSF-REU summer project and selected results are reproduced here [116]. Figure 6.36 presents the inverse pole figure data obtained from the EBSD scan of two butterfly structures. The different colored features represent different orientations of martensite and austenite crystals, the black dots are the inclusions, and the darker finely pixelated regions are the wings. The EBSD scans were inconclusive in regard to confirming the nano-grained nature of the butterfly wings as reported in literature [33]. The wings were unable to be indexed, presumably, due to a combination of the supposed fine grained structure of the wings, the high dislocation density of the wings, as well as interference due to the crack associated with the wings. By inspection of Figure 6.36, the butterfly wings/cracks propagate through the original microstructure with no apparent preferential orientation and the original microstructure is transformed into the wing microstructure. This observation is not dissimilar from the literature and supports the stress related formation mechanism of the butterfly wings [14, 17].
A schematic illustration of the method/location used to prepare the TEM lift outs of the butterfly wings using FIB milling is shown in Figure 6.37a. The milled sample analyzed during the NSF REU summer work was selected from a gas carburized 4120 specimen which failed by scuffing, rather than pitting, after 0.6 million cycles. Figure 6.37b shows a schematic of the lift out and the location within the lift out analyzed by TEM. The fine grained microstructure of the butterfly wing is shown in Figure 6.37c. Figure 6.37d shows the electron diffraction pattern obtained from the microstructure in Figure 6.37c. The ring-like pattern observed indicates that the microstructure scanned contained fine subgrains [117], which is consistent with the literature (Figure 6.38 [33]). The substructure in the 4120G appeared somewhat more coarse than the butterflies examined by Grabulov [33]. Further analysis of the diffraction pattern, in Figure 6.37, confirmed that the fine grains were ferritic. This analysis was performed by comparing the inverse of the ratio of the diameters of the circles to the ratio of the spacing (d spacing) between allowed \{hkl\} planes \((h^2+k^2+l^2 = \text{even number})\). An example of the d spacing ratio calculation for the \{110\} and \{200\} planes is shown in Equation (6.1).

\[
\frac{d_{(110)}}{d_{(200)}} = \frac{a}{\sqrt{h^2+k^2+l^2}} = \frac{\sqrt{4}}{\sqrt{2}} = 1.414
\]  

(6.1)

where “a” is the lattice constant for ferrite. Using \{110\} as the reference and assuming that it was represented by the first reflection (inner diffraction ring) in Figure 6.37d, the other diffraction rings were indexed. The diameter ratios corresponded well with the allowed reflections for ferrite.
Figure 6.37  (a) Schematic illustration of location and orientation of FIB lift out used for TEM analysis of butterfly wing found in a 4120G specimen. (b) Schematic illustration of FIB lift out showing cross section of wing microstructure analyzed by TEM. (c) Bright field TEM image of white etching wing showing fine grained, dislocated microstructure below the surface corresponding to the white etching wing. (d) Diffraction pattern created by fine grained ferrite wing microstructure.

A similar analysis of the butterfly microstructure produced during contact fatigue was made by Grabulov et al. [33]. The results of their TEM investigation of a FIB lift out of a butterfly wing produced during a pure rolling contact fatigue (RCF) test of 52100 steel are given in Figure 6.38. The RCF tests were carried out at a nominal contact stress of 2.6 GPa and a test temperature of 100°C (212°F). The differences in the diffraction pattern of the matrix and butterfly wing are apparent. The coarse grained matrix created a discrete diffraction pattern. The wing microstructure had ring-like patterns similar to those observed in this work. As mentioned above, the ring patterns created by the butterflies produced during RSCF testing in this work were more discrete than the ring patterns observed during RCF produced butterflies observed by Grabulov indicating that RSCF butterfly wing microstructures may be coarser than those produced by RCF, possibly due to the higher contact shear stress due traction associated with RSCF testing, or the differences in alloys examined, nominal contact stress, etc.
Figure 6.38 TEM cross section of a butterfly wing (from literature) formed in 52100 steel during RCF showing the difference in microstructure between the steel matrix (left) and butterfly wing (center and right). The diffraction patterns of locations corresponding to location A and B in the white box on the right side of the micrograph are representative of fine nano-grained ferrite. The grain size of B is larger than A. Reproduced from work of Gabulov et al. [33].

6.5 Incremental Testing Analysis

The results of the incremental RSCF testing of the vacuum carburized 4120 and 4320 are presented in this section. Gas carburized 4120 and 4320 could not be evaluated as not enough specimens were available after RSCF pitting evaluation. Incremental RSCF tests were performed using the same testing parameters as the RSCF tests conducted to failure. Four tests were conducted for both conditions suspended at 1,000, 10,000, 100,000, and 200,000 cycles. The results of the wear track and microstructural investigation are presented below.

6.5.1 Wear During Incremental Testing

The results of the profilometry scans of the wear tracks of the vacuum carburized 4120 and 4320 specimens after incremental tests are presented in Table 6.6, Figure 6.39, and Figure 6.40 which show the wear track depths, morphology of the 4120V, and morphology of the 4320V tests, respectively. The gas carburized 4120 and 4320 conditions were not included due to the lack of available test specimens. There were differences observed between the two alloys. These differences may have contributed to the observed differences in RSCF behavior.

Table 6.6 Maximum wear track depth of incremental RSCF testing of vacuum carburized 4120 and 4320.

<table>
<thead>
<tr>
<th>Number of Cycles</th>
<th>Wear Track Depth (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>4120</td>
</tr>
<tr>
<td>1,000</td>
<td>6.0</td>
</tr>
<tr>
<td>10,000</td>
<td>7.5</td>
</tr>
<tr>
<td>100,000</td>
<td>13.0</td>
</tr>
<tr>
<td>200,000</td>
<td>14.0</td>
</tr>
</tbody>
</table>
Figure 6.39 Wear track profiles of vacuum carburized 4120 incremental RSCF tests suspended at (a) 1000 cycles, (b) 10,000 cycles, (c) 100,000 cycles, and (d) 200,000 cycles. Tilt term filtered from optical profilometry analysis.

The vacuum carburized 4120 generally exhibited more wear at a given number of cycles. The morphology of the incremental wear tracks was similar and also comparable to the wear tracks measured after the RSCF tests conducted to failure; the width and curvatures of the wear profiles were relatively uniform and symmetric. Comparing the wear track depth at 200,000 cycles for the vacuum carburized 4120 (14.0 µm) to wear tracks measured for the failure tests (approximately 900,000 cycles and wear depths between 15 and 20 µm) it is proposed that the wear continued in the 700,000 cycles after the 200,000 cycle increment to reach the wear depths measured in the RSCF specimens tested to failure of 15 to 20 µm. A steady state run-in condition might not be developed and continual fatigue damage (deformation and cracking) might thus be more likely to occur in the vacuum carburized 4120. If run-in is
able to develop in the vacuum carburized 4120, it did not occur until after 200,000 cycles. However, only one test was able to be conducted at each increment and the number of test replicates may be insufficient to make a firm conclusion about run-in.

The vacuum carburized 4320 samples exhibited lower wear than the 4120 initially (at 1,000 cycles) and the wear depth appeared to saturate early at 10,000 cycles. Like the wear tracks measured from the failure RSCF tests, the depth and curvature of the 4320 wear tracks of the incremental tests were not as uniform or symmetric as the 4120. Considering that the longest RSCF life measured for the vacuum carburized 4320 test 11 (2.3 million cycles) had a measured wear depth of (only) 10.5 µm, it could perhaps be concluded that the longer pitting life was enabled because the wear track reached a steady state run-in condition early in the fatigue test, the steady state condition was maintained, and the
development of fatigue damage was diminished. Conversely, in the case of the shortest 4320 test 12 (about 0.5 million cycles) the wear track had a measured depth of 20.4 µm, a non-uniform morphology, and the wear appeared localized. It was speculated that the run-in condition, possibly represented by the 10,000-200,000 cycle wear profiles, was disrupted by local wear, continual wear and fatigue damage occurred, and early pitting was observed. As with the 4120V condition, the number of test replicates may be insufficient to be able to make a strong hypothesis about the run-in behavior or the 4320V subject to RSCF. Also, the residual stress profile and dislocation density (and changes to both after incremental testing) were not measured. These considerations may be important to improve the strength of the proposed explanation.

The evolution of the contact stress due to wear and plastic deformation of the wear track was considered by estimating a curvature of the wear track based on its width and depth according to Equation (6.2). The results are given in Figure 6.41.

\[
R = \frac{D}{2} + \frac{W^2}{8D}
\]

where \(R\) is the radius of curvature (negative mm), \(D\) is the wear track depth (in mm), and \(W\) is the wear track width (in mm). Equation (6.2) assumes that the wear curvature is circular.

![Figure 6.41 Estimated change in Hertzian contact stress during testing, based on pure rolling conditions from the nominal 3.2 GPa contact stress calculated for the sample and load roller geometry at the onset of RSCF testing, due to observed changes in wear track geometry from wear and plastic deformation.](image)

The contact stress decreases during run-in, but there was little change after 1000 cycles. After 10,000 cycles and beyond, as the wear track width and depth increase, the contact stress decreased from 3.2 GPa to about 2.8 GPa by 200,000 cycles. As the sample wear track curvature decreased, from an infinite value assumed due to the cylindrical geometry of the RSCF sample, to (negative) 300 to 400 mm (estimated radius of wear track curvature), the conformity between the load roller and sample would have
increased leading to a reduction in the contact pressure. From this analysis, the nominal contact stress (at the beginning of the RSCF tests) was found to change early in the fatigue tests.

The alteration in the surface roughness of the wear tracks was also measured using optical profilometry after incremental RSCF testing. Combining this roughness change with the change in surface roughness of the load rollers before and after testing, the evolution of the lambda ratio was also determined. The results of the analysis are presented in Figure 6.42. The sample surface roughness changed rapidly at the beginning of RSCF testing, reaching a relatively constant value as early as 1,000 RSCF cycles. The evolution of the lambda ratio was similar. The lambda ratio increased initially and saturated as early as 100,000 cycles. The difference between the time to achieve the steady sample surface roughness and steady state lambda ratio is thought to be due to the influence of the load roller roughness.

![Figure 6.42](image)

(a) Change in RSCF sample and load roller surface roughness (μm roughness average, Ra) and (b) lambda ratio of vacuum carburized 4120 and 4320 during incremental RSCF testing at 3.2 GPa nominal contact stress, 100°C, and -20 percent slide.
on the lambda ratio calculation. The load roller surface roughness was not observed to reach a steady state value until approximately 100,000 cycles. The lambda ratios were observed to double in value (from about 0.13 to about 0.26). Tallian [37] showed that lubrication does not exhibit a large effect on contact fatigue lives until the lambda ratio reaches a value of 0.8. Therefore, the change in the lambda ratio during testing may not have had a significant impact on the fatigue lives. Even so, the incremental testing roughness results indicated that the initial conditions changed quickly, and were not representative of the majority of the RSCF test.

Secondary electron SEM was also used to investigate the evolution of the appearance of the wear track. Figure 6.47 presents representative micrographs from the 4120V incremental tests. The surface profiles of the vacuum carburized samples exhibited vacuum grooving of the prior austenite grain boundaries in the as heat treated condition, a phenomenon that was reported by Bykowski [44]. After 1,000 RSCF cycles (Figure 6.43b), the majority of the grooving had been worn/deformed such that only the deepest grooves were still visible. After 10,000 cycles (Figure 6.44c) the vacuum grooving was no longer visible and abrasive wear features became more apparent. After 100,000 cycles (Figure 6.45d) the surface appeared smoother, but the circumferential abrasive wear marks were still apparent. After 200,000 cycles (Figure 6.46e) the wear track surfaces were relatively featureless, some abrasive wear features were still visible. From the perspective of the appearance of the wear tracks, it did not look as if that a steady state appearance was reached until 100,000 to 200,000 cycles. A significant amount of wear was observed initially, however, by inspection of the difference between the appearance of the wear track prior to RSCF testing and that of the 1,000 and 10,000 cycles wear tracks. It would have been interesting to evaluate the effects of IGO on the incremental behavior of carburized RSCF samples, unfortunately no comment can be made regarding the effect of IGO as no gas carburized specimens were available for incremental testing.

6.5.2 Butterfly Formation and Cracking During Incremental RSCF Testing

LOM and SEM were used to determine whether butterfly structures form during the initial cycles of RSCF testing. Since butterflies were observed in even the shortest RSCF tests conducted to failure, it was of interest to understand when, and how they developed. The metallographic investigation of cross sections of the vacuum carburized 4120 and 4320 incremental tests revealed that butterflies began to form between 10,000 and 100,000 cycles for both conditions, as shown in Figure 6.52. After 1,000 cycles no cracking was observed around non-metallic inclusions when investigating wear track sections in the as-polished condition using SEM. After 10,000 cycles microcracking around inclusions was observed in the
Figure 6.47 Representative secondary SEM images of wear track profiles of vacuum carburized 4120 during incremental RSCF testing. (a) onset, (b) 1,000, (c) 10,000, (d) 100,000, and (e) 200,000 cycles. Rolling direction up.
as-etched condition as viewed using LOM. Microcracking was found in the as polished condition using SEM. No white etching features were observed around the microcracking at 10,000 cycles (Figure 6.53a shows microcracking around inclusions before etching and Figure 6.53b shows the same inclusion after etching). At 100,000 cycles butterflies were found. SEM investigations confirmed the presence of a microcrack with the white etching feature (Figure 6.54 shows microcracking around inclusions before etching and Figure 6.54b shows the same inclusion after etching). Because the wings were always observed around the cracks after 100,000 cycles it is hypothesized that the wing and microcracks develop and propagate cooperatively and the microcrack is necessary for the development of the white etching feature, consistent with the literature [14, 15].

Butterflies were more common in the 4120V 100,000 cycle test than the 4320V 100,000 cycles test. Butterfly wings were only observed around large clusters of inclusions, which would act as more severe stress concentrators than a singular inclusion, in the vacuum carburized 4320 after 100,000 cycles, which may indicate the higher cracking resistance of the vacuum carburized 4320, assuming that butterfly formation is a cracking-related feature. After 200,000 cycles butterfly features were more numerous in both alloys. The size of the cracks and wings around inclusions were observed to have increased from the 100,000 cycle tests. Like the butterflies observed in the RSCF tests conducted to failure, the butterflies/cracks produced during the incremental tests were observed to propagate nearly parallel to the rolling direction. The mechanism through which cracking allows butterfly formation is not clear, either in the literature, or in the results obtained during this work.

Based on the results of the butterfly investigation of RSCF tests conducted to failure and incremental tests, a simplistic model of butterfly formation leading to microcracking and micropit formation at 3.2 GPa nominal Hertzian contact stress, 100°C lubrication, and negative twenty percent slide ratio was developed. This model ignores the formation of WEC not associated with non-metallic inclusions. A pictorial schematic of the model is given in Figure 6.56. At the onset of RSCF cycling (Figure 6.48a), there are random distributions of non-metallic inclusions located in the microstructure, some located at depths corresponding to the maximum shear stresses from contact. Between 1,000 and 10,000 cycles (Figure 6.49b) cracks nucleate and grow from some of the non-metallic inclusions located near the surface and at depths up to 700 µm. Between 10,000 and 100,000 cycles (Figure 6.50c), localized microstructure change of the parent martensite occurs leading to the formation of white etching fine structures around the micro cracks. It is speculated that these butterflies either grow, due to crack propagation, or remain stable if the crack does not propagate after further cycling. The crack and wing structure grow somewhat cooperatively Figure 6.51d), the white etching wing structure lags behind crack. The growing crack/white etching feature could be considered a WEC. The crack propagation may be
Figure 6.52 Light optical micrographs of incremental RSCF tests of vacuum carburized 4120 and 4320 suggesting progression of butterfly growth. (a) 4120 and (b) 4320 microcracks at 10,000 cycles. (c) 4120 and (d) 4320 butterflies observed at 100,000 cycles. (e) 4120 and (f) 4320 butterflies observed at 200,000 cycles. Rolling direction and surface orientation indicated by long black arrow. Transverse view. Picral etch.
Figure 6.53  Field emission secondary electron scan of microcracking around non-metallic inclusions from incremental testing of 4320V after 10,000 cycles. (a) As-polished. (b) Same location after etching with picral, no wing structure visible. Rolling direction and surface orientation indicated by long black arrow.

Figure 6.54  Field emission secondary electron scan of microcracking around a non-metallic inclusion from incremental testing of 4120V after 100,000 cycles. (a) As-polished. (b) Same location after etching with picral, wing structures visible. Rolling direction and surface orientation indicated by long black arrow.

arrested once it has extended far enough from the inclusion such that the combination of stresses from the inclusion/matrix modulus mismatch (which is only present in the near vicinity of the inclusion) and applied shear stresses from contact, is no longer of sufficient magnitude to encourage crack growth. Once a crack/WEC has grown far enough, two possible situations may occur which would allow the crack to encounter the wear track surface, spall off, and form a micropit. The first is that the crack simply grows until it reaches the surface (Figure 6.55e). The second case would occur if the crack/WEC was stable
but wear from the RSCF test caused the wear track to deepen until it encounters the crack tip (Figure 6.57f). Micropitting may then occur if the cracked material spalls off. Macropitting may also occur from either, or a combination of these cases if lubricant is allowed to flow into the crack, become trapped, and
then develop internal hydraulic pressure leading to a Mode I crack opening situation as suggested by Way [82].

6.6 Rolling Versus Rolling-Sliding Contact Fatigue

This section presents the results of the wear and microstructural evolution differences observed between tests conducted on each of the four material/heat treatment conditions under RSCF and rolling contact fatigue (RCF) conditions developed by removing the gear box (forced sliding) from the RSCF machine. The comparison between RCF and RSCF was conducted to investigate differences in wear and potential butterfly formation.

Comparing the extent of wear, it was found that minimal wear occurred during the RCF tests as compared to the RSCF tests as shown in Figure 6.58. The wear track depth of each RCF test, run for the same number of cycles as the average RSCF life measured for each condition, never exceeded about 4 µm. Clearly the RSCF test facilitated abrasion that was not present in RCF. However, recalling that sliding increases contact stresses due to the addition of the tractive force [94], the plastic deformation induced by the RSCF tests was most likely even higher than that of the RCF tests. It was unclear how much abrasive wear contributed to the development of the wear tracks observed after the RSCF tests conducted to failure, and how much of the wear track profile was created by plastic deformation of the worn surface.

![Figure 6.58](image)

Figure 6.58 Comparison of typical wear track profiles between (a) rolling contact fatigue test of gas carburized 4120 and (b) RSCF test 8 of gas carburized 4120.

LOM was performed on transverse cross sections of the RCF wear tracks to investigate possible butterfly formation due to RCF and compare the butterflies formed with those produced during RSCF tests. Butterflies were observed in each RCF wear track cross section, except for the gas carburized 4320.
There were far fewer observed in the RCF samples as compared to the RSCF samples (by orders of magnitude). Over one hundred butterfly features were observed in the wear tracks of the vacuum carburized 4120 and 4320 and gas carburized 4120 specimens subject to RSCF. Less than ten were observed in the gas carburized 4320 RSCF specimen. Very few (less than ten) butterflies were observed in the RCF tests conducted for the vacuum carburized 4120 and 4320 and gas carburized 4120. Again, no butterflies were detected in the gas carburized 4320 sample subject to RCF. No WEC were observed in the RCF samples.

There were differences observed in the appearance of the butterflies formed during RCF as compared to RSCF produced butterflies. The microcracks and wing structures in RCF were oriented at a much steeper, characteristic angle to the rolling surface/direction than the RSCF butterflies. In RSCF, the butterflies and cracks were typically oriented close to parallel to the rolling direction/surface. In RCF, the butterflies and cracks were oriented approximately 45° to the rolling direction/surface as shown in Figure 6.59 which includes butterflies observed during the 4120V, 4320V, and 4120G RCF tests. The observed difference in orientation of butterflies between RSCF and RCF may be due to the effects of sliding on the imposed stress state. The 45° angle associated with the RCF butterflies may be influenced by the octahedral shear stresses induced by rolling contact which are oriented at 45° to the rolling direction. Sliding changes the alternating orthogonal shear stresses which occur in-front-of and behind the contact. These orthogonal shear stresses act parallel, and perpendicular to the rolling direction/surface. Sliding appeared to increase the influence of these alternating orthogonal stresses on butterfly formation in RSCF.

The location in the transverse cross section of the wear tracks where butterflies were observed was different between RCF and RSCF butterflies. Figure 6.60 shows, schematically, the depth ranges where butterflies were observed superimposed on the etched microstructure profile for the 4120V steel from Figure 6.1. RSCF butterflies were found at the surface and at depths up to about 700 µm. RCF butterflies were only observed in a narrow depth range, between about 200 and 400 µm deep. These differences were thought to be influenced by the effect of sliding on the location, depth, and magnitudes of the maximum shear stress profiles. In RCF, the maximum shear stress occurs at some local depth beneath the surface (calculated based on pure rolling to be 428 µm for the current work). Above and below this depth the shear stress decreases rapidly which may explain why the butterflies in RCF were only observed in a small depth range. In RSCF, the sliding component increases the maximum shear stresses and according to calculations presented by Norton [94], the range of depths were the maximum shear stress occurs due to rolling and sliding contact remains relatively constant over a larger range of depths near the surface. The observed larger range of butterflies due to RSCF was thus believed to be due the alteration of the subsurface shear stress profile due to sliding according to Norton [94].
Figure 6.59 Light optical micrographs of butterflies produced during pure rolling tests using the RSCF machine with the gear box disengaged. Fatigue tests suspended at the average RSCF life of each condition for comparison. (a) Vacuum carburized 4120 0.877 million cycles, (b) vacuum carburized 4320 1.314 million cycles, and (c) gas carburized 4120 1.770 million cycles. No butterflies observed in gas carburized 4320 after 3.708 million cycles. Arrows indicate rolling direction and surface orientation. 1000X original magnification. Transverse view. Picral etch.

6.7 Summary

The carburizing treatments of the 4120 and 4320 RSCF samples produced martensitic case microstructures containing some RA and core microstructures that contained martensite, bainite and Widmanstätten ferrite. NMTP were also found in each of the four material/heat treatment conditions. The NMTP associated with the vacuum carburized samples was thought to be due to the lower cooling rates developed by the nitrogen gas quench. An equal amount of NMTP was observed in the 4120 and 4320 steels near the surface and in the bulk of the case. The NMTP observed in the gas carburized samples was due to decreased surface hardenability associated with oxidation of manganese to form IGO. Less NMTP was observed in the gas carburized 4320. The NMTP was thought to lower the magnitude of the
compressive residual stresses measured by XRD. Slightly increased carbon contents from vacuum carburizing increased the amount of RA observed in the vacuum carburized samples.

The vacuum carburized samples appeared to have lower RSCF resistance than the gas carburized samples for the RSCF conditions selected for this study. The 4320 may have been more resistant to pitting than the 4120 samples, possibly due to increased cracking resistance. Unfortunately, not enough fatigue tests could be performed to allow a statistical analysis of the RSCF lives to be carried out for a more accurate comparison of the pitting resistance of the four conditions studied.

The incremental analysis of the vacuum carburized 4120 and 4320 samples revealed the evolution of the wear track profile and surface roughness during RSCF testing at the conditions employed in this study. The initial surface roughness of the vacuum carburized samples was quickly worn/deformed away leading to a steady state surface roughness and lambda ratio in the first several thousand RSCF cycles. The wear behavior of the various conditions, in regard to the development and ability to maintain a steady state run in wear track morphology was thought to influence the RSCF behavior.

Butterfly features were observed in all fatigue samples. Differences in the resistance to butterfly formation for a particular condition were shown to correspond to RSCF pitting lives. The microstructure of the white etching butterfly wings was shown to be ferritic with fine substructure, consistent with a similar observation in the literature. Through incremental testing of vacuum carburized 4120 and 4320, it was found that microcracking and white etching features grew cooperatively around non-metallic inclusions leading to butterflies. The butterflies were observed at 100,000 cycles. Comparisons between RSCF and RCF developed butterflies revealed differences in morphologies and depths of observation that were related to the alteration of the contact stresses from sliding.
CHAPTER 7: CONCLUSIONS

The objectives of this research were to understand the effects of vacuum and high temperature gas carburizing on pitting fatigue resistance of two commercial gear steels and to understand damage evolution leading to pitting, as evaluated using a rolling-sliding contact fatigue (RSCF) machine. A secondary objective was the modification of the rolling-sliding contact fatigue machine to address problematic aspects of its original design. For the heat treatment and contact fatigue conditions considered in this study, the following conclusions, based on the research objectives as well as on additional observations, were made:

1. There was no apparent benefit on increased pitting resistance resulting from vacuum carburizing over gas carburizing. In fact, pitting resistance was decreased presumably due to the formation of non-martensitic transformation products in the carburized case, and the associated reduction in magnitude of compressive residual stresses, as a result of the lower cooling rates developed by nitrogen quenching. Additional test replicates may be necessary to confirm the observed behavior.

2. Macropitting was observed to result from cracking as a result of micropitting and near-surface microcrack formation. The formation of butterfly structures was shown to contribute to the micropitting and microcracking. Pitting lives were shown to decrease when the propensity for butterfly formation is increased.

3. The initial surface roughness and contact stress were shown to change over the course of rolling-sliding contact fatigue testing as a result of wear and plastic deformation. The surface roughness was shown to change rapidly in the first 1,000 cycles.

4. It is postulated that the ability of a carburized sample to maintain a steady state run-in condition may result in an increase of the pitting fatigue life. The samples with the longest pitting lives had wear track profiles, at the time of pitting, comparable in appearance and depth to the apparent steady state profiles observed during incremental testing.
5. Microcracking appeared to be necessary for the formation of butterfly wing structures because microcracking was observed around inclusions before white etching wings were found and the wings were never observed without a corresponding microcrack. The cracking and white etching structures appeared to grow cooperatively with the white etching wing slightly lagging behind the crack tip. The butterfly features were observed to develop between 10,000 and 100,000 cycles.

6. The orientation and depth of butterfly formation was shown to be dependent upon the applied shear stress resulting from the contact type (rolling versus rolling-sliding). The butterflies developed during RSCF testing were oriented nearly parallel to the rolling direction and observed in a greater range of depths possibly due to an influence of traction from sliding on the orthogonal shear stresses which are oriented parallel and perpendicular to the rolling direction. The butterflies observed after pure rolling testing were oriented at nearly 45° to the rolling direction at a specific depth close to the maximum octahedral shear stress which also occurs at 45° to the rolling direction.

7. Modifications to the rolling-sliding contact fatigue machine at the Colorado School of Mines have been made to improve the reliability of the machine in regard to pitting evaluation. These modifications include:
   - Increased capability to adjust sample alignment for the reduction of load fluctuations on the sample and damage to the machine during testing.
   - Improved reliability of lubrication during testing by preventing the development of starved contact using a circulating, filtered, gravity feeding delivery of heated oil.
   - Improved control of the hydraulic load and added test suspension capability in response to abnormal conditions that could invalidate the fatigue test through a modified control program.
CHAPTER 8: FUTURE WORK

The goal of this project was to develop a deeper understanding of the rolling-sliding contact fatigue (RSCF) resistance of gear steels subject to vacuum and gas carburizing through evaluations of the pitting lives and the evolution of damage developed by RSCF that may lead to pitting. Unfortunately due to a shortage of undistorted fatigue specimens leading to a lack a test replicates (especially for the gas carburized conditions) and a shortage of time available to complete the proposed test matrix, a comprehensive understanding of the pitting behavior of the carburized steels was not developed. Therefore, the following additional research was proposed:

1. Conduct additional RSCF tests to failure on specimens subject to a similar gas carburizing treatment employed in this work to increase the database and comparison between pitting resistance of the vacuum and gas carburized conditions. This should aid understanding the effects of intergranular oxidation on RSCF pitting.

2. Use higher hardenability steels or employ oil quenching as opposed to gas quenching for the vacuum carburized condition to reduce the amount of non-martensitic transformation products (NMTP) in the vacuum carburized condition for a better comparison between the vacuum and gas carburized conditions to reduce the possible influence of the NMTP.

3. Conduct additional incremental tests for each condition to more carefully examine the hypothesis regarding the influence of run-in on RSCF behavior. In addition, monitor possible alterations in residual stress and dislocation density during incremental testing.

4. Continue to characterize the butterfly features using EBSD and TEM during incremental testing to further understand the mechanism of their formation as it relates to microcracking.

5. Conduct tests on RSCF specimens carburized to similar case depths at conventional carburizing temperatures to evaluate to benefits/drawbacks associated with increased carburizing temperature employed in this work.
Additional changes to the RSCF machine are recommended to improve additional problematic aspects of its design that could not be addressed during this work while carrying out the proposed test matrix. These changes (discussed in detail in Appendix C) include:

1. Improvement of RSCF sample design and/or fixturing to reduce the influence of distortion and lower cost.

2. Replace the rigid chuck used to grip and rotate the RSCF sample with a constant velocity joint (double U-joint), and fix the sample support head to the RSCF machine rather than using a floating, linear support system tied to the hydraulics, to improve alignment and lower wear of the machine during testing.

3. Evaluate the design of, and possibly replace, the gear box to improve sliding control and reduce the propensity for non-uniform slipping leading to artificial wear and fatigue failure.
REFERENCES


[32] A. Grabulov and H. W. Zandbergen, “TEM and Dual Beam (SEM / FIB) Investigations of Subsurface Cracks and White Etching Area (WEA) Formed in a Deep Groove Ball Bearing Caused by Rolling Contact Fatigue (RCF).”


[101] “Personal Correspondance with Scott Hyde of The Timken Company.”


APPENDIX A: ROLLING-SLIDING CONTACT FATIGUE MACHINE MANUAL

A.1 Introduction - Rolling-Sliding Contact Fatigue Machine Test Set-up and Preparation

The following outlines and details important operating procedures for the rolling-sliding contact fatigue (RSCF) machine at the Colorado School of Mines. Included are step-by-step guides to prepare the machine for RSCF testing, a guide to run the LabView program used to operate and monitor the RSCF tests, and a procedure for shutting the machine down. Also included are visual references of all relevant tools and parts.

A.2 Load Roller

Follow these instructions to install a load roller onto the RSCF machine prior to testing.

A.2.1 Load Roller Assembly

Refer to Figure A.1 below for necessary parts and to Figure A.2 for required tools for load roller assembly.

Figure A.1 Parts required for load roller assembly: (a) new or refinished load roller, (b) 2X 5/16 1 ¼” hex head wire lock-able bolts, (c) 2X lock washers, (d) one piece mounting 2” ID shaft collar, (e) 2” load roller shaft, (f) load roller shaft extension, (g) 2” pin, and (h) retainer ring.
Figure A.2 Tools required for load roller assembly: (a) ¼” and 1/16” hex wrench, (b) thread locker (Loctite), (c) thread locker primer, (d) stainless steel wire (e) safety wiring pliers, and (f) dremel tool with grinder (not shown).

First ensure that the threads of the bolts and shaft collar are clean, use a de-greasing agent if necessary. Do a preliminary assembly without thread locker to check the orientation of the safety wiring bolt holes. Thread the bolts with the locking washers until they are tight (do not over tighten). The shaft collar should be oriented so that the side with the threads intersecting the collar surface, not the counter bore, is touching the load roller. The bolts go through the holes in the load roller and then thread into the shaft collar. The safety wiring holes should be oriented similar to Figure A.3. Bolt A should be oriented such that an imaginary line through the safety wiring holes is pointing, somewhat, into the center of the load roller. Bolt B should have its holes oriented so that a similar line points tangentially to the assembly; this will allow for easier safety wiring. Now, insert the load roller shaft into the center hole to check that it will slide relatively easily into the load roller and collar assembly. If it does not fit try loosening the bolts, slipping the load roller shaft into the assembly and retightening. It may be necessary to assemble the load roller with the shaft through the center bore to ensure that the load roller shaft fits into the assembly.

Next, use the dremel tool to grind a groove near the inward facing hole of bolt A in a manner similar to Figure A.4. The groove should be deep enough to allow the safety wire to be wrapped around the bolt without touching the load roller shaft. The groove makes installation easier and prevents stress concentrations in the wire which can cause premature failure. After grinding, disassemble the load roller
and shaft clamp assembly and clean each part to remove metal powder from grinding.

Once cleaned, apply primer followed by thread locker (Loctite) to the bolts and reassemble the load roller and collar exactly as before. Again, tighten the bolts but not excessively. Allow approximately one hour for the thread locker to harden. The time it takes for load roller installation, main shaft alignment, sample alignment, and oil heating will consume this time.

Figure A.3 Orientation of safety wire holes in 5/16” bolts for easiest safety wiring and load roller installation.

Figure A.4 Bolt A (a) before and (b) after grinding using dremel tool showing the orientation of the groove necessary to allow safety wiring of the load roller assembly.

A.2.2 Safety Wiring

Safety wiring, if done correctly, will prevent both bolts from loosening due to vibration during RSCF testing. If one bolt begins to loosen the other bolt will be torqued such that it is tightened.
Unwind about 12” of the safety wire from the safety wiring kit and insert half of it through bolt A as shown in Figure A.5(a). Note: bolt A always refers to the bolt that is ground using the dremel and is the first bolt threaded by the safety wire. Next wrap the end of the wire point away from the load roller clockwise around bolt A as shown in Figure A.5(b). Using the safety wiring pliers, grip the ends of the wire and lock the pliers. Twist the wire until the twist is close to that depicted in Figure A.5(c). Insert the load roller shaft into the center of the assembly and wrap the twisted wire counter-clockwise around the shaft. Unwind the end of the wire until it can be inserted into bolt B and be wrapped tightly around the shaft as shown in Figure A.5(d). Do not insert wire completely into bolt B yet. Take the load roller shaft out. The roller is ready for installation on the load roller head of the RSCF machine.

![Figure A.5](image)

(a) (b) (c) (d)

Figure A.5 Safety wiring: (a) thread wire through bolt A, (b) wrap wire clockwise around bolt A, (c) twist using wire twisting pliers and then unwind to allow a (d) taught wrap counter clockwise around the load roller shaft.

### A.2.3 Load Roller Assembly Installation

Refer to Figure A.6 for parts and tools required for load roller installation.
Figure A.6  Parts and tools required for Load roller installation: (a) load roller assembly from above, (b) ¼” hex wrench, (c) medium torque tube, (d) needle-nose pliers, (e) snap-ring pliers, (f) safety wire pliers, (g) snap ring, (h) 2X 2” ID thrust bearings, and (i) ¼” key.

First, check the number of cycles that have been applied to the roller bearings in the load roller test head. This will be about ¼ of the main shaft/sample rotation cycles. Replace the bearings after ~10 million cycles. Next, insert the load roller shaft snap ring groove side first into the test head from the gear box side of the test head. Push the shaft through the load roller assembly and one of the thrust bearings. The load roller assembly should be oriented such that the 2” shaft collar is on the main shaft side and the wire locking bolts are on the gear box side in the test head. The thrust bearing should be between the 2” shaft collar and the test head. Refer to Figure A.7. Using needle nose pliers put the key into load roller shaft keyway and orient the shaft keyway to line up with the keyway in the load roller assembly before pushing shaft all the way into the head. Push the load roller shaft all the way through. Place the second thrust bearing on the end of the shaft sticking out of the main shaft side of the test head. Use the snap ring pliers to install the snap ring. Figure A.7 shows the final assembly.

Once the snap ring is in place, thread one of the wire ends of the safety wire through bolt B. Pull it tight with the safety wire pliers. Make sure to only pull the end of the wire to not introduce stress concentrating gouges anywhere else on the wire. Pull the gripped length of wire so that it wraps slightly clockwise around bolt B. Now twist the two ends tight as before, making sure that the wire not threaded through the bolt holes wraps counter-clockwise around bolt B. Use the wire twisting pliers to cut the end
of the wire and bend it so it will not contact the oil splash guards.

Use the hex wrench to tighten the 2” shaft collar onto the load roller shaft. It is very important that when the collar is fully tightened that the load roller shaft is not loose at all in the axial direction. The load roller must also not “wobble” when it rotates. To avoid this, back-up the load roller when tightening the collar by applying an opposing moment when turning the hex wrench. To fully tighten the collar, use the medium torque tube on the end of the hex wrench but do not tighten so much that the load roller “wobbles”.

The load roller is now installed in the RSCF machine. Be sure so keep the load roller surface clean and avoid marking or scratching it at all costs.

Figure A.7  Installation of load roller in load roller head showing final assembly.

A.3  Lubricating Oil Cleaning/Replacement Procedure

Follow this guide to either add new oil/lubricant to the oil circulation system to be used for RSCF testing or to clean the oil following a RSCF test.

During the course of RSCF testing, ferrous particulates will accumulate in the oil due to wear of the sample and load roller. If these particles enter the contact zone premature failure can occur. Therefore, it is necessary to remove the particulates after each fatigue test. The following outlines the procedure.

First, remove the return tubing from the oil reservoir 1-gallon bucket and remove the lid. Note that the oil feed assembly remains attached to the lid. Empty the oil into a clean 5-gallon bucket. Take care that the switch magnets at the bottom of the 1-gallon reservoir do not fall out with the oil. Using a
switch magnet with a long hex head bolt threaded into it, stir the oil that has been emptied into the 5-gallon bucket with the magnet activated. Stir for about twenty seconds, pull the magnet out, let oil drain off, turn off the magnet, and clean it with a paper towel. Repeat this at least three times. Inspect the magnet and towel carefully. There should be very little, or no ferrous particles on the magnet or towel. If the magnet and towel are dirty (black) after cleaning, the oil needs to be changed. The oil should be changed after six tests regardless.

Next remove the three switch magnets from the bottom of the oil reservoir 1-gallon bucket. Do this without turning off the magnets. Once removed, turn them off and clean thoroughly. Spray the inside of the reservoir with de-greasing cleaner and clean with a cloth. Replace the magnets at the bottom of the clean reservoir. Two should be placed near the oil feed and two should be placed near the oil return.

The magnets placed in the oil catch beneath the contact area of the RSCF machine should be cleaned as well. Use one of the clean magnets to pick up ferrous particles that may still be present in the oil catch pan by moving it over the pan surface. Use a paper towel to wipe down the support rollers and all metal surfaces on the support and loading heads. Refer to Figure A.8.

Put the return tubing back into the reservoir lid and feed it through the smaller clamps. Pour the cleaned oil from the 5-gallon bucket back into the reservoir. Replace the feed assembly in the larger clamps and put the lid back on. Make sure that the return and feed tubing are not kinked. The oil is ready for the next RSCF test.

![Figure A.8](image)

Figure A.8  (a) Oil catch, (b) support rollers, (c) support head, and (d) load roller head (load roller not installed).
A.4 Rolling-Sliding Contact Fatigue Sample Installation

Follow this guide to install a bar sample into the RSCF Machine.

A.4.1 Sample Assembly

Refer to Figure A.9 for the necessary parts for RSCF sample installation. First, decide the orientation of the sample for RSCF testing. Slip the sample retainer on the end of the sample furthest from the testing location. The teeth of the sample retainer should be oriented toward the opposite end of the sample. Line up the retainer hole closer to the flat end of the retainer with the holes bored on the end of the sample. Insert the tapering pin. Figure A.10 shows the completed sample assembly.

![Sample Assembly](image)

Figure A.9 (a) RSCF carburized sample, (b) sample retainer, (c) tapering pin, and (d) chuck T-wrench.

Ensure that the RSCF Chuck jaws are opened wide enough to allow the sample retainer to slide in. Insert the sample with the retainer into the chuck. Align the three recessed notches (not the teeth) of the retainer with the three chuck jaws. Ensure that the flat end of the retainer is contacting the back of the chuck plate. Use the chuck T-wrench to close the jaws onto the sample. When jaws have just made contact with the sample surface, pull the sample outward as far as it will go (pull out of chuck). It should slide ~1 mm or so. Now tighten the jaws firmly using the T-wrench. RSCF sample installation is complete (refer to Figure A.11).
Figure A.10  RSCF bar sample assembly ready for RSCF testing.

Figure A.11  RSCF bar sample installed into RSCF machine 3-jaw adjustable chuck.
A.4.2 Sample Alignment

Sample alignment is one of the most crucial steps in ensuring the success of RSCF testing and preventing excessive noise and machine wear/damage. The following outlines the alignment procedure as well as tips and tricks for successful alignment.

The tools and parts needed for sample alignment are shown in Figure A.12.

First, pull the support head of the RSCF loading assembly as far back as it can go on the rails and use the c-clamp to hold it in place and out of the way for the alignment procedure (see Figure A.13). Position the dial gage and magnetic base as shown in Figure A.14. The needle of the dial gage must be placed on the location of the sample which corresponds to where the load roller will contact the sample. Also, the needle must be aligned perpendicular to the sample surface. Ensure that the dial can be seen for observation of eccentricity.

Use the large pulley on the main shaft to turn the sample several times. Observe the extent of eccentricity. The desired goal of the alignment is a maximum dial gage reading of ± 0.001” (± 1 gage mark). Using proper alignment techniques, eccentricity as low as ± 0.00025” have been achieved. Mark the end of the sample on the side exhibiting the lower end of the run out/eccentricity.
Figure A.13  Position of c-clamp to move support head back, allowing for ease of sample alignment.

Figure A.14  Dial gage positioned on RSCF sample for alignment.
Tip for alignment ground samples: Most RSCF samples should be alignment ground on the ends to fit the universal yoke bore. In the ground state, the side of the sample exhibiting the highest dial gage eccentricity value will be visible; it will have the highest “lip” at the edge of the ground sections. The lowest section which will be on the opposite side will have no “lip”. In this case, use the dial gage to measure the natural eccentricity of the chuck. Determine the lowest dial gage value and mark the corresponding circumferential position on the chuck. Loosen the sample in the chuck using the T-wrench and spin the sample so that the highest part of the sample (the side with the highest lip) lines up with the dial gage value mark on the chuck. They may not be perfectly aligned due to the requirement for the sample retainer teeth recesses to align with the chuck jaws. This method of rotating the sample in the chuck is another way to slightly alter the alignment.

If the eccentricity is low enough (±0.005” or so) it may only be necessary to adjust the adjustable chuck set screws (Figure A.15) using the ¼” hex wrench and medium torque tube.

There are four set screws on the adjustable chuck. By tightening a set screw, the surface of the sample in the same circumferential position as the set screw will “rise” slightly resulting in an increase in the eccentricity at that point. The idea is to find the position on the sample when it is turning that corresponds to the lowest reading on the dial gage (lowest eccentricity) and tighten the nearest one or two
set screws on the chuck to move the sample closer to center. If needed, utilize the medium torque tube to increase the amount of torque and thus center displacement applied. The amount of possible adjustment is lower when the chuck back plate bolts are fully tightened.

It is often necessary to loosen all six of the chuck back plate bolts slightly to allow for a larger range of chuck motion and adequate sample alignment. After loosening all six bolts, follow the same procedure as above. The use of the torque tube is usually not required when the bolts are loosened. Once the sample is aligned, retighten the chuck back plate bolts. To do this, use a “star” tightening pattern as shown in Figure A.16. Tighten each bolt slightly and use multiple passes through the pattern to fully tighten the bolts. At least three “star circuits” should be employed to ensure the chuck is tight and the sample alignment is maintained.

The alignment procedure is meticulous and will require experience and knowhow to be done correctly and quickly. Proficiency is achieved through trial-and-error and practice.

Figure A.16 Schematic of star pattern tightening order to tighten chuck back plate bolts after aligning the sample. Only tighten the outer bolts. The inner bolts are used to hold the chuck together.

A.4.3 Main Shaft Alignment

The main shaft may need to be aligned to ensure that the sample contacts the support rollers evenly and is level. High contact stresses can develop on the sample due to contact with the edges of the support rollers if the sample is not aligned evenly with all four rollers. Also, excessively high load fluctuations can develop. To determine if the main shaft needs to be adjusted, remove the c-clamp from the support head of the RSCF machine. Push the support head firmly into the sample such that all four support rollers are contacting the bar. While maintaining contact, observe the contact points between the support rollers and the sample closely. If an air gap is visible in any of the four contacts the main shaft
needs to be adjusted. The sample should be rotated and the extent of contact should be observed again to check different radial positions of the sample. *Note, with the current design of the RSCF machine, perfect alignment of the main shaft with the four support rollers is nearly impossible. The following procedure should be followed to align the main shaft “as best as possible”.*

First, loosen all four bolts on the two pillow block bearings (Figure A.17) and unhook the pulley belt from the tensioner under the machine top plate. To start, pull the main shaft using the aluminum extensions and pillow block bearings as far as it will go toward the support head side of the machine. Use this as the starting configuration. The lateral alignment may need to be adjusted; however, the adjustability of the gear box is able to account for lateral misalignment.

![Image of machine components](image)

**Figure A.17** Four large bolts to be loosened during main shaft alignment of RSCF machine. Arrows indicate location where shim tabs need to be inserted for leveling/alignment.

Retighten two of the large bolts, one on each of the pillow block bearings. Use the large torque tube and the large hex wrench to tighten moderately so the shaft does not shift. Push the support head into the sample until all four support rollers appear to be contacting the sample. Maintain this position and look at the contacting areas between the support rollers and the sample as before. If the shaft is aligned properly, there will be no air gap visible in any of the contact zones when viewed from any angle. The most likely reason that air gaps exist between the sample and one or more of the support rollers is that the main shaft is not level.
A level orientation can be achieved by inserting tabbed shims into the locations indicated by Figure A.17. As with sample alignment, the leveling and aligning of the main shaft assembly can be very meticulous and will require significant trial and error to be done correctly. After the main shaft has been aligned, retighten all four of the large bolts on the pillow block bearings. Like the chuck bolts, do not tighten one at a time but rather tighten the bolts in circuits a little at a time. To ensure that they are fully secure, use the large torque tube to apply maximum torque. Unlike sample alignment, the main shaft assembly should not have to be aligned for every test. Only align the shaft if air gaps are visible on the aligned sample. Sometimes, the sample alignment may need to be readjusted (using chuck set screws according to the procedure above) after main shaft alignment.

*Remember: reattach the tensioner to the pulley belt after the main shaft is bolted down securely.*

### A.5 General Test Preparation

After load roller installation, sample and main shaft alignment, the hydraulic arm pin needs to be inserted into the hydraulic arm and the oil magnets filters, oil splash guard, and load roller need to be installed.

#### A.5.1 Oil Filtration Magnets

Relatively cheap, flat magnets or switch magnets can be purchased from McMaster-Carr©. They should be placed into the oil catch pan on the RSCF machine around the drain as shown in Figure A.18. The purpose of these magnets is to reduce the risk of oil contamination from small, hard ferrous particles removed during wear and pitting. These magnets should always be cleaned thoroughly before and after each RSCF test.

![Magnets](image.png)

Figure A.18 Typical orientation of magnets around oil drain to filter out ferrous particles.
A.5.2 Oil Splash Guard and Hydraulic Arm Pin

See Figure A.19 for the parts and tools required for installing the oil splash guard and hydraulic arm pin.

![Figure A.19](image)

Figure A.19 (a) Splash guards side R and L, (b) U-pin, (c) long \(\frac{1}{2}\)" bolts, washers, and nuts, (d) wrench, (e) ratchet, (f) 1" ID large rubber seals, and (g) hydraulic arm pin.

First, slip the R splash guard over the sample, flat side first. Slip two 1" ID large rubber seals onto the sample. They must be aligned carefully so that they are positioned just outside of the support rollers where they will not contact either the support rollers or the splash guards. Next, slid the L splash guard over the sample with the “lipped” side first.

Now the hydraulic arm needs to be connected using the large pin. Inspect the hydraulic actuator located underneath the RSCF machine. There is a black mark on the actuator shaft. This mark should be either barely visible or completely hidden inside of the actuator. If it is not, the arm is extended too far for assembly and will need to be retracted. To do this, turn on the MTS control panel located to the right of the RSCF machine. Once it is on, hit ENTER which will bring up the select display message. Hit the DISPLAY button on the RSCF terminal. If any red error lights are on, simply hit reset. Ensure that the light next to SET POINT is on. It should read close to 0.00V. To bring the hydraulic arm back, the applied voltage must be negative. Turn the hydraulics from OFF to LOW. This should turn on the
hydraulic pump. By turning the dial counter clockwise, decrease the voltage to -20V or so. *Never turn on the hydraulics when the voltage is non-zero to prevent shock and damage to the hydraulics.* Look to make sure that the hydraulic arm is retracting slowly. Allow it to retract until the black mark is barely visible and turn the hydraulics from LOW to OFF, turn the applied voltage back to 0.00 V, and shut off the MTS control panel. Figure A.20 shows the MTS control panel with arrows indicating the order to retract the actuator arm. Move behind the machine and insert the hydraulic arm pin as shown in Figure A.21.

![MTS control panel](image)

*Figure A.20 MTS control panel visually outlining steps to retract hydraulic actuator arm for hydraulic arm pin insertion.*

Now that the hydraulic pin and arm is in place, the load roller should be nearly in position next to the sample. Using the large ½” bolts, washers, and nuts, install the splash guards as shown in Figure A.22. Do not over tighten the bolts. Once installed, insert the U-pin into the top lips of the R and L splash guards to hold them together.
Figure A.21  Installed hydraulic arm pin also showing actuator arm with black mark mentioned previously. Located below aluminum base plate of RSCF machine.

Figure A.22  Installed splash guards on support head of RSCF machine.
A.5.3 Gear Box Installation

The machine components and tools necessary for gear box installation are shown in Figure A.23. It is critical to check the sample gear shaft in the gear box prior to RSCF testing to ensure that no fatigue cracking has developed which can invalidate the test. The sample gear shaft is prone to fatigue because of the relatively high number of cycles it experiences, its smaller diameter, and the stress concentration imparted by the machined 1/8” keyway. To check for cracking, remove the front-left retainer plate on the gear box using the 1/8” t-wrench to remove the four retainer plate bolts (see Figure A.24). It is important that the retainer plate is installed in the same orientation as it was removed otherwise reinstallation can be difficult. Do not remove the sample double U-joint. Keep the assembly together. Once the retainer plate is removed, pull out the bearing and remove the shaft and small helical gear. The entire assembly is shown in Figure A.25. Remove the small helical gear. This may be difficult due to wear and scuffing of the gear shaft. Once the gear and 1/8” key are removed, clean the small gear shaft thoroughly. Inspect the shaft, especially around the keyway, for fatigue cracks. An example of a fatigue crack is pictured in Figure A.26.

![Figure A.23](image-url) (a) Assembled RSCF gear box with double U-joints attached, (b) gear box ½” bolts, washers, and nuts, (c) ¾” wrench, (d) Loctite, (e) primer, (f) high viscosity gear oil (not shown), (g) ¼” and ¾” hex wrench, (h) 1X⅜” and 1X3/16” keys (2X 3/16” keys already installed on gear box shafts, and (i) 1/8” t-wrench.
Figure A.24  Front left retainer plate on RSCF gearbox.

Figure A.25  Sample gear box extension assembly removed from gear box.
If a large crack is visible, replace the shaft. The assembly can be reinserted into the gear box once the shaft is checked/replaced. Always be cautious not to spill the lubricant out of the gear box during removal and reinstallation. Do not over tighten the retainer plate. The gearbox is now ready for installation.

First, set the gear box and double U-joints onto the gear box extension plate. Insert the ¼” key into the sample keyway. Slip the sample U-joint assembly (1” bore side first) over the sample and key. It is recommended to install the sample double U-joint first. The load roller double U-joint can be more easily installed by pulling the keyed, ⅜” gear box shaft back, positioning the U-joint bore and keyway in alignment with the keyed load roller extension shaft, and pushing the gearbox shaft forward. Due to wear, fretting, and gouging from the set screws, it may be difficult to slide the load roller double U-joint onto the load roller extension shaft. Simply use a file to smooth the shaft. A soft headed hammer can also be employed to connect the U-joint. Once the double U-joint assemblies are slipped over the shafts, bolt the gear box to the gear box extension plate. Do not tighten bolts completely yet. Adjustment s will still be made. Figure A.27 shows the gear box installed on the RSCF machine. The Loctite and primer will be used after the hydraulics have been turned on. The preliminary set-up for RSCF testing is now complete.

*Hint: the load roller gear extension shaft can slide in and out of the gear box. This can be used to the RSCF tester’s advantage when installing the load roller double U-joint assembly. The shaft can be pulled back and then inserted more easily into the U-joint bore without tilting the gear box backwards. After installation remember to remove the collar on the load roller gear shaft.*
A.5.4 Gear Replacement

The gears will need to be replaced periodically, especially the smaller gear due to wear and pitting. The small gear can be replaced by removing the small gear/shaft assembly as above in the inspection of fatigue cracking. Replacement of the larger gear is more complex. The oil will need to be drained. Once drained, place the gearbox on its side with the front plate/U-joints facing up. Remove the right front bearing retainer plate. Pull out the bearing and shaft. The large gear will remain inside the gear box. Be careful not to lose track of the 3/16” key. Once the shaft is removed the larger gear can be pulled out of the gear box. Unlike the smaller gear, the larger gear cannot be flipped around in the current gear box design. Remember, a left hand helical gear meshes with a right hand helical gear. So if the smaller gear is a left hand gear, the larger gear must be a right hand gear, and vice versa.

The new larger gear needs to be machined prior to installation. The center bore must be increased to 0.750” to allow it to be slipped onto the gear box shaft. Also a 3/16” keyway must be broached into the expanded bore. The CSM machine shop lathe and broaching machine have these capabilities, especially considering the relative softness of the gears.

Once the larger gear is machined, slip it into the gear box with the hub facing toward the back of the gear box (down). Center it around the right bearing bores, slip the keyed 0.750” shaft into the center bore (with the 3/16” key), and replace the load roller U-joint assembly. As before, maintain the position...
of the bearing retainer plate to ensure that it will fit. Replace the smaller gear/sample U-joint assembly. Right the gear box, and fill the gear box with oil until the level is just above the site glass view.

A.6 Final Rolling-Sliding Contact Fatigue Testing Setup

A.6.1 Turning on the Hydraulic System

As before, turn on the MTS frame. Press ENTER and press DISPLAY on the RSCF terminal. Ensure that SET POINT is lit up. Press RESET if any red error lights are lit up. Ensure that the SET POINT reading is close to 0.00 V. Turn the hydraulics from OFF to LOW. *Never turn hydraulics on with the voltage reading a non-zero (or close to it) value.* Let the load roller come into contact with the sample. Turn the hydraulics from LOW to HIGH. Note: the pump turning on/switching from low to high should be audible. The hydraulics must be on HIGH before the LabView program can be run.

A.6.2 LabView Program Startup and Oil Bath Heating

Open the LabView RSCF program. The program as it will appear when opened is shown in Figure A.28. Always ensure that the hydraulics are on HIGH pressure. Press the start button (white arrow in upper left task bar). The program will prompt the location to store the data collected during testing. It will save two data files. The first data file records the test time, number of cycles, load, temperature, and mean vibration every 10 seconds. The second file will save the hydraulic voltages and test time. The ability to save either of these data files can be turned off by clicking the two buttons in the lower right indicated in Figure A.28. Once this is done the program will start. Once started the program defaults to State 1. Figure A.29 shows the onscreen view of State 1. Ensure that the oil reservoir HEATER ENABLED light is OFF (green light not on) and that the OIL RESERVOIR temperature is at room temperature. Turn the Oil Pump on (manually using the on off switch near the suspended reservoir on the RSCF machine) and allow the suspended reservoir to fill completely. Leave the pump on. The float switch in the reservoir will shut the flow off as needed. Turn on the oil bath heaters from the LabView program once the oil reservoir is full by clicking HEATER ENABLED button.

Monitor the oil bath temperature. Once it approaches 70°C, open the flow valve and allow the oil to flow onto the load roller. *Make sure the oil pump is on!* Use a low flow rate at first to let the oil heat up. This heating process can take up to an hour. In the meantime, place the main guard (larger plastic guard that covers the main shaft assembly) on the machine, being careful to avoid sharp edges.
Figure A.28  LabView RSCF Program as opened. The start button and data save commands are indicated by the arrows.

Figure A.29  LabView RSCF Program State 1. The arrow indicates the oil heater on/off switch control.
A.6.3 Tightening Double U-Joint Set Screws and Gear Box Bolts

First, ensure that the double U-joints are as straight as possible by adjusting the gear box laterally. Once this is done, tighten the gear box to the gear box extension plate using the large bolts on each side. Unscrew each set screw on the double U-joint assemblies and clean thoroughly to remove dried Loctite. Be careful to prevent the dried Loctite residue from falling into the oil catch pan. Once the set screw is clean, apply a small amount of primer using the brush and then apply the Loctite. Tighten the set screw with the 3/16” hex wrench. Repeat for the remaining three set screws. Check to see that the set screws between the two universal joints for sample and load roller are tight; if loose, remove and reset with primer/Loctite and tighten screws. Also, make sure that the gear box is full of gear oil. The site glass should be completely submerged by gear box oil. Do not over fill.

After all set screws are tightened and the gear box is bolted down, place the smaller plastic guard over the machine. Figure A.30 shows the machine with both guards in place. Now, allow the oil bath to heat up until the temperature of the oil coming out of the nozzle above the load roller is nearly 100°C as indicated by the State 1 pane of the LabView program. Once at temperature, increase the flow rate of the oil to a moderate flow, but not so much that hot oil is spraying everywhere. At this point, the mechanical aspects of the machine are ready for RSCF testing.

Hint: place rags and cloths over the gaps on the top and sides between the two plastic guards to prevent oil from spraying out all over the hydraulics lab walls and floor.

Figure A.30 RSCF machine with both plastic guards in place.
A.7  LabView Program and Testing

This section presents the operating/testing procedure for the RSCF machine using the LabView program.

A.7.1  State 1 – Start

As stated above, State 1 is the default state of the RSCF program that will start when the program is run. The various panes, inputs, and outputs pertinent to State 1 are shown in Figure A.31. The only aspect of the machine that can be controlled from State 1 is HEATER ENABLED (on/off). The VIBRATION TRIP SET POINT can also be edited. It is a good idea to set this at a value of 0.8 for starting up the test. Once the steady state vibration is known, the set point can be changed, more on this below. The purpose for State 1 is to monitor the oil bath temperature as it heats up.

![Figure A.31  LabView RSCF Program State 1.](image)

A.7.2  State 2 – Motor

Once the oil is heated, hydraulics are on HIGH, and the machine is ready for testing press the NEXT STATE button in the LabView Program. Doing so will start State 2. State 2 is used to start the motor/rotation and ramp up the hydraulics/load. First, press the button MOTOR COMMAND to ensure that the motor has power, the lights will come on. There is an entry box with a “0” in it labeled MOTOR
SPEED. This entry box has a maximum value input of “10”. Below the MOTOR SPEED input is a STATE 2 LOAD slider. At the beginning of State 2, the voltage induced by the slider will be 0.25. The Force applied by the load roller should increase immediately at the beginning of State 2. See Figure A.32 which shows the pertinent panes, inputs, and outputs in State 2. Ramp the MOTOR SPEED up from 0 to 2 to 4 to 6 to 8.55 (8.55 is nearly 1000 rpm, this final value will change based on the size of the pulley belt and tension applied by the tensioner). At the same time steadily increase the STATE 2 LOAD from 0.25 to 1.5V. Once the MOTOR SPEED is at 8.55 and the STATE 2 LOAD is at 1.5 the machine is ready for STATE 3.

![Figure A.32 LabView RSCF Program State 2.](image)

**A.7.3 State 3 – Full Pressure**

State 3 is the Full Pressure state. Once the NEXT STATE button is pushed during State 2 activating State 3, the hydraulic voltage will jump from 1.5 to just below 2V. This final voltage can be adjusted based on the desired contact load. 2V corresponds to a load/force of 3000 lbf. 0V corresponds to ~0 lbf. The desired load to achieve 3.2 GPa nominal contact stress is 2,959 lbf which corresponds to an input voltage of 1.973V. Nothing else needs to be changed during State 3. The vibration often spikes at the start of each RSCF test and then falls as the sample and load roller reach their steady-state run-in conditions. It is advised to allow the initial vibration spike to occur and then fall to a steady state value
during State 3. Once the steady state vibration is reached (usually after 20,000-50,000 cycles) the machine is ready to move to State 4.

A.7.4 State – 4 Testing

State 4 is the testing state of the RSCF LabView program. The only difference between State 3 and State 4 is that the VIBRATION TRIP SET POINT becomes important. If the MEAN VIBRATION ever exceeds the VIBRATION TRIP SET POINT value the machine will shut off and move to State 5, shutdown. State 5 can also be activated if the OIL FEED temperature exceeds 110°C; which can occur if the oil stops feeding into the reservoir and the oil overheats. The MOTOR SPEED, HEATER ENABLED, and VIBRATION TRIP SET POINT can all be adjusted during State 4. Figure A.33 presents the panes of the LabView State 4 that are important. It is critical that the machine is never left in operation in State 3. Always move the program to State 4 before leaving the machine running for an extended period of time.

![LabView® RSCF Program State 4](image)

Figure A.33 LabView® RSCF Program State 4. Important panes/inputs are (a) STOP MACHINE, (b) STOP ENTIRE PROGRAM, (c) TOTAL REV, (d) MEAN/RAW FORCE, (e) HEATER ENABLED and oil temperatures, (f) MEAN/RAW VIBRATION, (g) VIBRATION TRIP SET POINT, (h) MOTOR SPEED, and (i) RPM.
The STOP MACHINE and STOP ENTIRE PROGRAM buttons are very important to understand and distinguish. They can both be pressed at any time. STOP MACHINE will send the machine program to State 5. Note: STOP MACHINE will not change any of the input values such as MOTOR SPEED or VIBRATION TRIP SET POINT and it will preserve the TOTAL REV as well as continue to record data to the desired location. In almost all cases STOP MACHINE should be used as opposed to STOP ENTIRE PROGRAM. STOP ENTIRE PROGRAM is an emergency hard stop and can cause issues with the program and data being recorded but will stop everything immediately. Again for emphasis: STOP ENTIRE PROGRAM should only be used in case of an emergency where there is an immediate risk to personal safety that would prevent the machine from being shut down properly using STOP MACHINE. If STOP ENTIRE PROGRAM is used, make sure that the MTS frame is turned off by turning off the surge protector to ensure that the oil heaters are powered down.

A.7.5 State 5 – Shutdown

State 5 is automatically achieved if the VIBRATION TRIP SET POINT value is reached by the MEAN VIBRATION value or if the OIL FEED temperature exceeds 110°C. From this state the program can be shut down once the TOTAL REV value is recorded. TOTAL REV is the number of cycles until pitting occurred leading to the RSCF machine shutdown. Press the STOP MACHINE button, turn the hydraulics from HIGH to LOW to OFF, turn off the MTS console, and then press the small red circle at the top of the LabView program task bar near the white arrow which was pushed to start the program at State 1. If the NEXT STATE button is pushed during while in State 5, the program will return to State 1.

A.8 Post Test Procedure

A.8.1 Cooling Down and Safety

The machine should be shut down using the procedure given above. At the end of testing, every component on the RSCF machine will be VERY HOT. Do not attempt to disassemble the machine right away. Wait at least one or two hours. Use oil resistant and/or cut resistant gloves when handling parts and tools. It is recommended to allow the oil/oil pump to run without the heater enabled during this time as well to let the oil and, most importantly, the heating elements in the suspended reservoir cool down.

There will be oil spread everywhere. Use rags to mop it up including degreasing cleaner to clean up any spills on the floor. The large plastic safety guards should be removed and placed on oil absorbent cloths out of the way. Be careful when handling the guards as there are sharp edges. Gloves are recommended.
A.8.2 Removal of Gear Box

The double U-joint assemblies should be loosened first by loosening the set screws on the sample/load roller side of the U-joints. Keep the set screws on the gear box shafts tight. This can be difficult as the Loctite has hardened significantly. Also, due to natural vibration in the gear box, there is often scuffing and fretting wear between the U-joint bores and the gear box shafts. This can make them difficult to remove without pulling the shafts out of the gear box which should be avoided. The shaft which tends to be the most problematic is the load roller extension shaft. It is not necessary to remove the double U-joints from the gear box assembly. Unbolt the gear box from the gear box extension plate and pull the gear box and double U-joints from the RSCF machine. Set aside.

Trick/Hint: Use a ¾” ID shaft collar as shown in Figure A.34. Unbolt the gear box from the gear box extension plate and move it forward slightly so that the gear box extension shaft extends out the back of the gear box toward the operator. Slip the ¾” collar around the shaft and tighten. Carefully pull the gear box out away from the machine. The U-joints should slip off. It may be necessary to use the soft head hammer. Remember to remove the shaft collar before the next test.

Figure A.34 Use of ¾” shaft collar to remove gear box from U-joint assemblies.

A.8.3 Removal of Load Roller and Sample

First, undo the large bolts holding the oil splash guards in place and pull them away from the support head so that when the hydraulic arm pin is removed the plastic guards will not be damaged or broken.

The same tools used for load roller installation will be needed for removal. A soft headed hammer is also recommended for removal. First, remove the hydraulic arm pin. Next, loosen the shaft collar and loosen the shaft enough so that it can slide out and the snap ring and thrust bearing can be removed. Then
pull the load roller support shaft out. This may require the use of the soft headed hammer. Be careful that the inner thrust bearing does not get caught in the snap ring groove, which can lead to bending of the bearing. Use pliers to remove the ¼” key. Be careful to not let the load roller drop when the shaft is pulled out fully. Cut off the safety wire and unthread the bolts holding the load roller to the shaft collar. This may require the use of a clamping vice to hold the load roller as the Loctite will have hardened significantly. Dispose of the bolts and safety wire.

Last remove the sample and splash guards from the RSCF machine and disassemble the sample assembly. Remember, two tests can be performed on each sample. Just connect the sample retainer on the opposite side.
APPENDIX B: UPDATED RSCF MACHINE PARTS LIST

B.1 Introduction

Following are schematic drawings for machining and parts lists for the rolling sliding contact fatigue machine. The drawings are meant to supplement those presented by Davis [89] and Melton [118] according to the modifications made to improve the RSCF machine reliability and performance. Electronic Solidworks drawings and PDFs are available and should be used for quoting.

B.2 Schematics

The following schematics are Solidworks drawings which outline the dimensions and tolerances of RSCF machine modifications. The schematics are organized according to the machine function they support. Note: additional machining requirements are always necessary when requisitioning a machining job; the Solidworks drawings will not stand-alone. In addition, tolerances may need to be adjusted. Tolerances can be discussed with the contracted machine shop during quoting.

B.2.1 Main Shaft Components

Additions to the main shaft include the main shaft itself, a new chuck back plate to accommodate the adjustable chuck, and the overall assembly of the main shaft and chuck back plate. The specifications for the main shaft are given in Figure B.1. Figure B.2 shows the specifications for the back plate. The final assembly drawing is shown in Figure B.3.

![Main Shaft Components Schematic](image-url)

Figure B.1 Main 20” shaft supported by pillow block bearings and press fit into chuck back plate. 1X
Figure B.2  Adjustable chuck back plate to be assembled with main 20” shaft. 1X

Figure B.3  Main shaft assembly for RSCF machine. 1X

B.2.2  Ground, Carburized Sample

The machining schematic for the alignment and tolerance ground RSCF sample is provided in Figure B.4. Note, if the sample run-out at its center is greater than 0.010” due to distortion, alignment and tolerance grinding may not be possible. If the run-out is excellent, (around 0.001”) only tolerance grinding will be necessary. Note: run-out refers to the change in height, relative to a reference, of the top of the curved part of the cylindrical sample as it rotates in an aligned apparatus such as a lathe.
Figure B.4  Alignment and tolerance grinding schematic for distorted RSCF samples post carburizing.

B.2.3 Load Roller Support Shaft and Shaft Extension

Figure B.5 and Figure B.6 give the dimensions and tolerances for the load roller support shaft and load roller shaft extensions, respectively. The two components are assembled with a 2” 0.250” diameter pin and aluminum retainer ring.

Figure B.5  Load roller support shaft drawing and tolerances for machining. 1X
B.2.4 Double U-Joint Coupling Shafts

The sample and load roller double U-joint coupling shaft drawings are given in Figure B.7 and Figure B.8, respectively.
B.2.5 Gear Box Components

The following provides the schematics for the gear box extension plate and some components of
the gear box. The components necessary for the gear box extension plate are given in Figure B.9 and
Figure B.10. The modified gear box component schematics are shown in Figure B.11 and Figure B.12.

Figure B.8 Load roller double u-joint coupling shaft. 1X

Figure B.9 Gear box aluminum extension plate. 1X
Figure B.10  Steel support plates. 2X

Figure B.11  Gear box aluminum modified base for extension plate. 1X

B.3 Parts Catalogue

Following is an inclusive table (Table B.1) providing the description, quantity, and source of various components than can be ordered as replacement parts for the RSCF machine. Some components, such as large socket-head-cap-screw (SHCS) bolts used on the load roller head, support head, and hydraulic arms are not included. These bolts are available on any industrial supply website. Measure the dimensions and threading prior to ordering.
Table B.1  RSCF machine parts list.

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APPENDIX C: FUTURE MODIFICATIONS RECOMMENDED FOR RSCF MACHINE

C.1 Introduction

Appendix C outlines recommended future modifications to the rolling-sliding contact fatigue (RSCF) machine to resolve problematic aspects of its design not addressed during this work. For clarity, the proposed modifications are only guidelines and are not necessarily representative of the final dimensions. Further design will be required to develop exact machining specifications/tolerances to implement the changes. The aspects to be addressed are:

- The first aspect that should be improved is the RSCF bar sample design. The current design (12” long, 1” diameter bar) is susceptible to distortion from carburizing. RSCF testing requires near perfect alignment to ensure reproducible testing and to prevent damage to the machine. The design also requires a relatively large amount of material.

- The second modification is related to the application of torque to the sample by the motor during testing. The current design employs a three-jaw chuck bolted to a shaft rotated by the motor. The sample is held “rigidly” by the chuck. The chuck is also used to align the sample for RSCF testing. Once the hydraulic load is applied to the sample, there is some displacement of the bar from the unloaded position as gripped by the rigid chuck. This displacement can alter the alignment of the chuck and sample preventing adequate alignment during RSCF testing. Also, because of the rigidity of the chuck connection, resultant forces/moments are developed in mechanical aspects of the machine that were only designed for the application of torque. The additional forces/moments cause degradation of the main shaft/pillow block bearings than can hinder alignment.

- The third aspect of the machine that should be addressed is the application and control of sliding during RSCF testing. Currently the slide ratio is developed using a gear box with gears purchased off the shelf. Poor tolerances specified in the current gear box allowed the slack in the gear meshing (no continuous meshing of the gear teeth during rotation). The poor meshing was observed to result in aggressive, periodic rotation of the load roller during some of the RSCF tests. The load roller would alternate between rolling and increased sliding as the surface velocity of the load roller increased and decreased, as opposed to a continuous slide to roll ratio of negative twenty percent. The aggressive periodic sliding resulted in high amounts of periodic wear/plastic deformation of the RSCF sample leading to artificial failure.
C.2 RSCF Sample Redesign

The proposed redesigned RSCF sample is presented in Figure C.1. To address the susceptibility of distortion of the current design, the RSCF sample will be shortened to 3” in length. The design consists of a center, 1” diameter by 1” long, portion which will be the location of the RSCF test. The ends of the sample have smaller diameters, and will be used for press fitting in the sample assembly. The as machined diameters of the press fit ends are larger than the final dimensions for press fitting. After carburizing, the ends can then be ground down both to achieve the necessary diameter for a strong press fit and to correct distortion from carburizing. The proposed design also uses significantly less material.

The RSCF sample will have connections press fit onto either side. A possible design of the connections is given in Figure C.2 and the final assembly is shown in Figure C.3. The connections will serve to connect the sample to the drive shaft and the gear system. The connections should be made from tool steel or vanadium alloyed 1045 for increased wear resistance and strength. The ID of the connections for the press fit assembly should be 0.0005” to 0.0008” smaller than the OD of the ends of the RSCF sample after post carburizing grinding.

The smaller sample design is only recommended for a single RSCF test (the current design allows two RSCF tests). This recommendation considers the time and temperature associated with RSCF testing. The lubricant is typically heated to 100°C, the sample temperature is most likely higher due to frictional heating, and each test can last for several days. Possible tempering may occur, which would make the material testing conditions of a second fatigue test different than the first.

Figure C.1 Schematic of redesigned RSCF specimen. (a) Pre-carburized dimensions. (b) Post-carburized grinding specifications for correction of distortion and press fitting. All dimensions in inches.
C.3 RSCF Sample Support and Torque Application Modification

The next aspect of the machine to be addressed is the sample support system to accommodate the redesigned press fit sample and to allow modification of the drive shaft/torque application. The current sample support head utilizes a “floating” hydraulic arm system that can travel freely and relies on the rigid chuck to provide the majority of the support of the sample. Also, the support head utilizes four roller bearings (support rollers) to support the sample and allow rotation during testing. The bearings cannot be aligned which is problematic for sample alignment during testing.

The proposed, simplified support head is shown in Figure C.4. The final design of the support head should allow it to be rigidly held to the RSCF machine to offset the entire compressive load applied by the load roller during testing. Instead of the support rollers, mounted bearings having the same ID as the OD of the sample press fit ends, would be used to support the applied load and allow rotation. The
bearings are self-aligning (part number listed in Table C.1) and can grip the sample evenly using three set screws. The support head would need to be aligned with the torque drive shaft. A constant velocity joint (CV joint) should be used to transmit the torque to the sample (Figure C.5). Unlike the chuck, the CV joint cannot support the applied load, and displacements during testing would not affect the sample alignment. Also because the applied load cannot be transferred to the drive shaft by the CV joint, additional damage to the drive shaft during testing should be minimized. Because the sample is no longer rigidly held by the drive shaft, the alignment of the drive shaft will not affect the sample alignment. Sample eccentricity, rather than alignment should be the primary contributor to load fluctuation.

Figure C.4 Proposed modification of sample support head. The support head should be rigidly connected to the RSCF machine rather than on linear, “floating” guides.

Figure C.5 Assembly of RSCF sample, sample support head, and constant velocity (CV) joint. CV joint to replace current chuck design for application of torque.
C.4 Modification of Controlled Sliding Mechanism

The controlled sliding mechanism (currently utilizing a gear box), should be improved or redesigned to reduce slack in the gearing and lower the propensity for aggressive, cyclic slipping during RSCF testing.

C.4.1 Modification of Existing Gear Box

The existing gear box system (simple schematic shown in Figure C.6) could be modified using the gear box plate drawings shown in Figure C.7 and Figure C.8. The updated drawings were designed for the gear box bearings (parts listed in Table C.1) to be press fit into the gear box plate bores to minimize the slack during gear rotation and meshing.

![Schematic of current sliding mechanism design utilizing gear box](image)

Figure C.6 Schematic of current sliding mechanism design utilizing gear box (gear box not shown, Double U-joint connections shown which transmit torque to and from the gear box).

C.4.2 Direct Connection of Gears to Sample and Load Roller Shafts

The second possible modification of the gear system is to eliminate the gear box and the shaft coupling system between the gear box and the sample/load roller. Gears could be attached directly to the sample assembly and load roller support shafts as shown in Figure C.9. In doing so, slack in the coupling system and misalignment between the gear box and sample/load roller shafts would be minimized. The gears could be lubricated in-situ using the current lubrication system.

Currently, stock gears are utilized for the gear box. The stock gears, although inexpensive and readily available, wear/pit quickly. They are also black oxide coated. The coating wears off quickly and contaminates the gear box lubrication. In order for the proposed alteration to be made, the gears would
need to be custom machined, carburized, and ground to improve the gear durability and prevent contamination of the lubrication system. Also, the load roller support shaft and one of the press fit sample connections would need to be altered to allow the gears to be directly connected.
C.4.3 Addition of Second Motor to Rotate Load Roller Shaft

The third proposed alteration to the sliding mechanism of the RSCF machine is to add a second drive shaft operated by a separate motor to rotate the load roller (Figure C.10). Like the sample drive shaft...
shaft, the load roller drive shaft would be connected to the load roller drive shaft using a CV joint. The advantage of the second drive shaft is that the number of possible applied sliding ratios is much larger because the load roller angular velocity can be set to nearly any value by the second motor. There are a smaller number of possible slide ratios that can be developed by the finite combinations of compatible gears. The disadvantage of an additional drive shaft is related to the added complexity of designing/installing the additional drive shaft and motor as well as improvement of the rotational speed measurement system. It is proposed to utilize a magnetic RPM sensor (Table C.1) to accurately set and monitor the sample and load roller angular velocities, which are critical for accurate sliding during testing.

C.5 Additional Parts for Proposed Modifications

Table C.1 gives the parts available for purchase to make the recommended RSCF machine modifications. Other supply sources besides McMaster-Carr may be considered.

<table>
<thead>
<tr>
<th>Part/Component</th>
<th>Source</th>
<th>Part Number</th>
<th>Quantity</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mounted Bearings</td>
<td>McMaster</td>
<td>2722T22</td>
<td>2</td>
<td>Sample Support Head</td>
</tr>
<tr>
<td>1.75” OD Bearing</td>
<td>McMaster</td>
<td>6384K369</td>
<td>3</td>
<td>Gear Box Plates, Front/Back</td>
</tr>
<tr>
<td>37mm OD Bearing</td>
<td>McMaster</td>
<td>5972K86</td>
<td>1</td>
<td>Gear Box Plate, Back</td>
</tr>
<tr>
<td>Magnetic Sensor</td>
<td>McMaster</td>
<td>65985K73</td>
<td>2</td>
<td>Magnetic Sensor (RPM)</td>
</tr>
</tbody>
</table>