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Surface hot-shortness of 1045 forging steel with residual copper

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Abstract

Hot-shortness is brittleness in metals during high temperature deformation. In this study, surface hot-shortness of 1045 steels with residual copper was investigated. Eight 1045 steels with differing copper contents, from 0.09 to 0.39% (by weight), were tested. High strain rate compression tests of pre-bulged samples were used to simulate forging deformation conditions. It was found that oxidation time and temperature are critical parameters for the control of hot-shortness. The testing was divided into two stages: stage one, in which the steels were oxidized at different temperatures from 1100 to 1200 °C for 10 and 30 min and subsequently deformed to determine the critical temperature where the surface cracking becomes severe; and stage two, in which the steels were oxidized for 1, 3, 5, and 7 min at their critical temperature, and then deformed. In the stage one testing, all steels oxidized for 10 min and subsequently deformed exhibited a critical temperature. The critical temperature decreased with decreasing copper content, from 1160 °C for the steel with the highest copper content to 1110 °C for the steel with the lowest copper content. A simple model based on copper enrichment and depletion along surface grain boundaries is presented to explain these observations. Steels oxidized for 30 min and subsequently deformed did not exhibit severe cracking at any temperature, but the steel with the highest copper content that was deformed at 1140 °C exhibited cracking. In stage two testing, the results were less consistent. The steels with high copper content (0.39–0.32%) exhibited maximum cracking at shorter times, while for the steels with medium copper content (0.30–0.21%) the maximum cracking occurred at longer times. No steel exhibited cracking when oxidized at 1200 °C and subsequently deformed. The study shows that steels have a critical temperature at which cracking is severe. Steels oxidized and deformed above the critical temperature did not exhibit hot-shortness surface cracking. Hence, a forging practice that both maintains and deforms the steel above the critical temperature could reduce or eliminate surface hot-shortness due to residual copper.

Keywords: Residual copper; Forging; Cracking; Steel; Hot shortness

1. Introduction

With the increased usage of steel produced from an electric arc furnace with its primary charge of scrap steel, copper residuals in forging steels are increasing; hence, there is a renewed concern about surface hot-shortness due to copper residuals.

Hot-shortness is not a new problem; it has been known since the early 1900s, when it was called red-shortness [1]. The topic arose again in the late 1950s and 1960s, when the amount of copper residuals increased in steels, and the steel industry encountered production problems [2]. In the late 1990s, the issue has once again taken on importance, mainly for economic and environmental reasons. Numerous studies and investigations have been performed to obtain a better understanding of the problem and minimize its detrimental effects.

There was a significant amount of research performed from the 1950s through the 1970s, in which the phenomenon was identified and studied in detail. Electron probe techniques were used to characterize the various elements involved and their relationship. These studies confirmed what had been previously assumed. In 1952, Gertsman and Tardif [3] catalogued various situations in which copper present in steels resulted in surface cracking. The cracking was worse if any significant amount of tin was present in the steel. They were the first to identify that the oxidizing atmosphere also has a major influence on the problem. Later, Melford [4] confirmed that specific residual elements caused hot-shortness. Tin was found to make hot-shortness worse, and nickel proved to be beneficial. He stated that residual elements are catastrophic, and developed an empirical equation for the amounts of those residual elements that prevent hot-shortness. Nicholson and Murray [5] investigated the influence of soaking time and atmosphere (varying oxygen content, water vapor, and SO_2 gas) by means of bend testing. For the first time, they found a critical temperature

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at which the surface cracking was most severe. Salter [6] determined the ternary phase diagrams of mild steel with Cu–Ni, Cu–Sn, and Cu–Sb. They demonstrated the existence of the liquid and solid phases in these ternary type systems.

Other research studies performed in the late 1960s and 1970s focused on the diffusion of copper in steels. These studies attempted to provide a more precise description of the predominant mechanism for hot-shortness via copper diffusion. These studies make clear that the diffusion of copper in steel at high temperatures is principally along grain boundaries. The studies also provide a more precise estimate of the solubility of copper in steel at high temperatures. An important conclusion resulting from these studies is that the diffusivity of copper increases considerably with increasing temperature [7–11].

In the late 1990s, there was a renaissance in the research on hot-shortness in copper-containing steels. The Journal of the Iron and Steel Institute of Japan International [ISIJ International 37 (3) (1997)] dedicated a complete issue of their publication to the copper–iron system. The studies presented in the issue of the journal show a new direction in the attempt to solve the problem, via processing strategies, rather than with alloy modification.

Imai et al. [12,13] provided a detailed description of the metallic compounds found in the scale, scale/metal interface and in the metal. They measured the contents of the elements in those compounds and identified the phases from the appropriate ternary phase diagrams. They state that the amount of nickel necessary to prevent hot-shortness is half of the copper content. This contrasts with what was published 20 years previously, which indicated the amount of nickel should be the same as that of copper to prevent hot-shortness. In addition, they found no surface cracking in the temperature range of 1200–1300 °C, with or without the presence of nickel. They also indicated that the surface produced by oxidation at high temperatures was highly uneven. The reason attributed for the absence of cracks at these high temperatures is the rapid diffusion of copper in austenite. The diffusivity of copper in iron is five times greater at 1200 °C than at 1100 °C. Seo et al. [14], investigated the surface hot-shortness in 0.1% C–0.5% Mn steels containing 0.5% Cu, by means of tensile testing at high temperature. They found that at 1100 °C, an addition of 0.4% Si or 0.02% P was effective in decreasing the susceptibility to surface hot-shortness. Although the oxidation rate was increased as a result at 1200 °C, the susceptibility to surface hot-shortness in all steels deceased compared with 1100 °C. At 1200 °C, for all steels, the oxidation rate was much higher than at 1100 °C, but the amount of copper-enriched phase at steel/scale interface was reduced compared with that at 1100 °C. Other research studies focused on the strain rate dependence of copper embrittlement in steels [15], and the influence of copper and tin on the hot ductility in steels [16].

The motive for these recent research studies is the need to find an economically viable solution for deforming steels with residual elements at high temperatures without cracking. Due to these economic factors, it would be highly desirable to provide a solution focused on processing changes, rather than alloy modification. From the previous studies, it seems that shorter heating times, controlled atmospheres in the furnaces, or higher working temperatures are some options worthy of further investigation.

2. Experimental procedures

2.1. Experimental steels

The steel used for this project is 1045, because of its simple chemistry and common utilization. It has a limited amount of alloy additions to confound the study. Table 1 presents the chemical compositions of the commercially produced steels, which were investigated. All the steels meet the specification for 1045, and they are identified as shown in Table 1 by their residual copper content. All the steels possessed a typical air-cooled, ferrite–pearlite microstructure. The average hardness of all the steels was 57 HRA.

Table 1
Chemical composition of the experimental 1045 steels (by wt.%)

Element	Steel							
	09	20	21	25	30	32	35	39
C	0.43	0.44	0.44	0.44	0.44	0.43	0.46	0.45
Mn	0.77	0.74	0.74	0.71	0.72	0.69	0.81	0.80
P	0.011	0.004	0.014	0.009	0.008	0.01	0.013	0.014
S	0.017	0.032	0.024	0.0193	0.0237	0.027	0.027	0.0153
Si	0.25	0.24	0.17	0.28	0.23	0.18	0.26	0.24
Cu	0.09	0.20	0.21	0.25	0.30	0.32	0.35	0.39
Ni	0.07	0.08	0.08	0.08	0.09	0.11	0.11	0.10
Cr	0.14	0.10	0.14	0.10	0.11	0.14	0.16	0.16
Mo	0.03	0.023	0.03	0.023	0.02	0.03	0.026	0.024
Sn	n/a	0.007	0.014	0.009	0.009	0.014	0.01	0.011
V	0.027	0.023	0.026	0.024	0.027	0.025	0.027	0.028

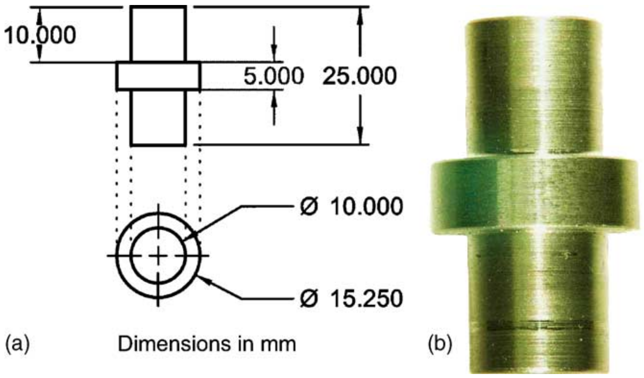


Fig. 1. Pre-bulged flanged test sample: (a) dimensions; (b) actual sample.

2.2. Testing methods

Specimens of the steels were compressed on a Gleeble 1500, a thermo-mechanical servo-hydraulic testing device. A flanged specimen was used. This is a pre-bulged specimen that has a larger diameter in the center to enhance the circumferential strain. See Fig. 1. Hot-shortness cracks develop because of surface tensile stresses. As the pre-bulged sample is compressed, the central section with the larger diameter expands and imparts circumferential tensile strain. The strain causes surface tensile stress, and cracking occurs.

2.3. The test matrix

The test temperatures ranged from 1100 to 1200 °C, where hot-shortness is reported both to occur and become critical. The lower temperature (1100 °C) is just above the melting point of copper and the higher temperature (1200 °C) is above the reported critical hot-shortness temperature [12–14]. The testing was separated into two stages.

In the first stage of the testing, the steels were oxidized at different temperatures for 10 and 30 min, temperatures were 1100, 1120, 1140, 1160, 1180, and 1200 °C. The steels were oxidized inside a furnace in air. After the oxidation treatment, the samples were air-cooled. Before reheating, the excess scale was removed using a wire brush. The samples were then heated in the Gleeble at a rate of 10 °C/s, held at the testing temperature for 30 s to stabilize, and deformed at the highest axial speed that resulted in a circumferential strain rate of 15 s^{-1}. The main objective of these tests was to determine the critical temperature at which the cracking is most severe. The critical temperature is defined as the temperature that exhibits the largest amount of surface cracking.

In stage two testing, the steels were tested at the critical temperature found in stage one, for varying oxidizing times. The focus of this stage of testing was to study and understand how oxidation time affects cracking. The samples were oxidized directly in the Gleeble. Samples were heated at a rate of 10 °C/s, then held at the testing temperature for 1, 3, 5, and 7 min, and then deformed at a circumferential strain rate of 15 s^{-1}. This stage was designed to simulate the conditions found in a forging practice that uses induction heating.

Finally, the two steels with maximum amount of residual copper (Steels 39 and 35) were oxidized for 1 min at 1200 °C (with heating rate of 10 °C/s). One thousand two hundred degree celsius is the maximum temperature of the test matrix. The test was performed to compare the results of the steels with low residual copper content deformed at their critical temperatures to steels with high residual copper content deformed at a high temperature. It should be noted that 1200 °C is closer to the actual working temperatures in forging operations.

2.4. Surface crack measuring techniques and analysis

In most of the samples, the cracking was distributed in groups, instead of being uniformly distributed around the whole circumference. This non-uniform distribution of the cracks could be attributed to a localized concentration of liquid copper, which when the sample is deformed causes localized cracks and the development of more strain in the local regions. The other factor contributing to the non-uniform distribution could be a slight asymmetry of the sample, resulting in non-uniform strain distribution. Fig. 2 shows an example of the crack distribution of a representative sample.

Experimental efforts were made to measure and quantify the surface cracks. Examination of the surface of a sample sectioned at its mid-height allowed counting and measuring of the width and depth of each crack that the cut intersects.

Crack measuring was done automatically using image processing techniques. Fig. 3 shows an example of how cracks are identified, measured, and counted. An image of the sectioned specimen was captured digitally. Since the only relevant information of the test specimen was the surface morphology, a contrast image via digital image processing was obtained. The contrast image revealed only the circumference with the cracking information. Each image contains more than 3 million pixels. The resolution of each pixel was approximately 20 μm, this puts a limit to the minimum crack size that can be identified and measured. To eliminate noise on the measurements, the depth of an identified crack had to be larger than a threshold value of 40 μm (or 2 pixels). As a result, the minimum crack size measured was 40 μm deep and 20 μm wide.

All digital processing was performed using Image J software developed by the National Institute of Health (NIH). Once the contrast image was produced from the digital picture, the brightness and the contrast were adjusted to obtain a clear circumferential silhouette. Every point on the circumference was stored in a data file. These data were then processed to produce a radius profile. A measuring routine counted each crack and provided width and depth data for each crack. A unit called "crack index" was defined. Crack index is the sum of the product of the width times

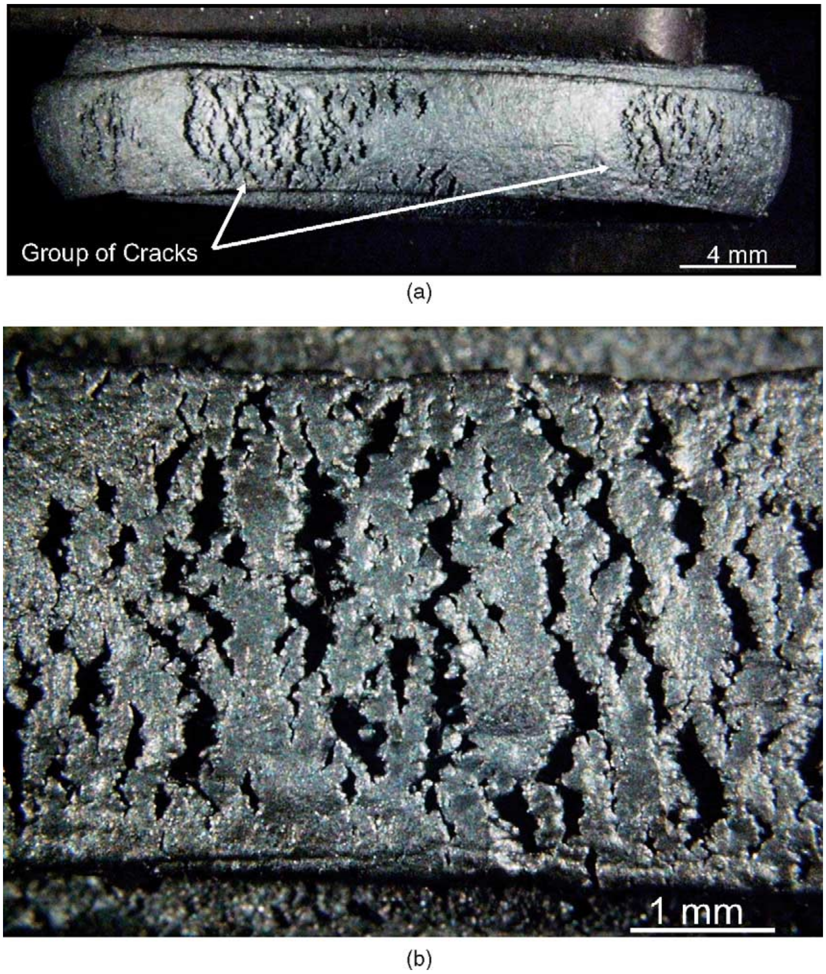


Fig. 2. Hot-shortness surface cracks of a steel with 0.35% copper, oxidized at 1160 °C for 10 min: (a) the cracks in groups; (b) close up of the surface cracking.

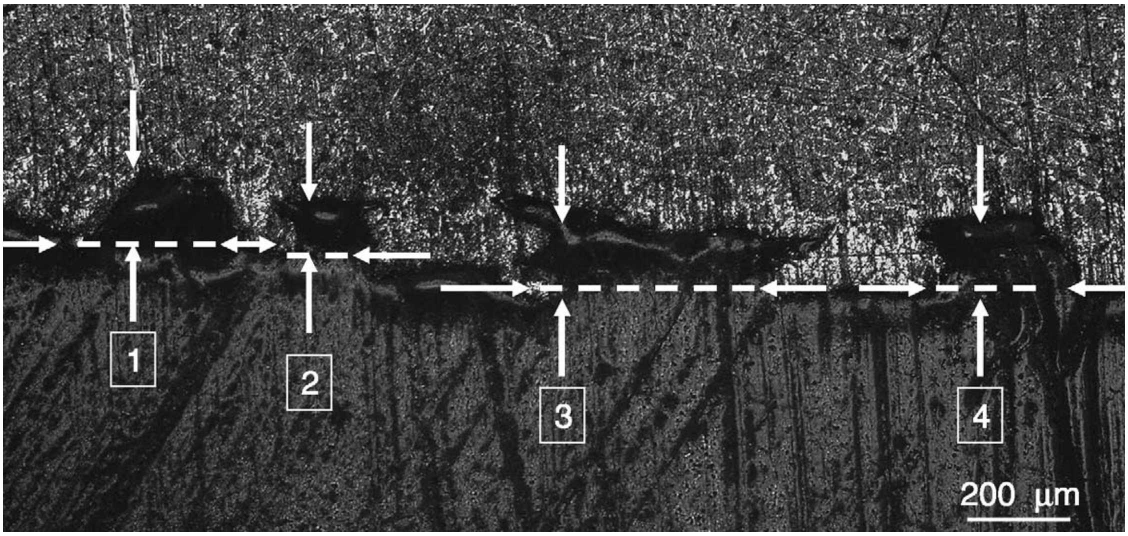


Fig. 3. Individual crack identification and measuring to determine the crack index. Four cracks are shown. Vertical arrows indicate depth and horizontal arrows indicate width.

the depth of each identified crack. The crack index calculation assumes that the crack has a rectangular shape. Fig. 3 shows that this assumption is reasonable. The crack index has units of area (i.e. mm^2) and provides a good representation of the surface cracking conditions. The crack index accounts for both the size and the number of cracks on the surface.

3. Results

The results of the present work are separated in two parts, corresponding to the two testing stages.

3.1. Stage one results

Fig. 4 presents the photographs for Steel 39, which was oxidized for 10 min and deformed. The photographs illustrate that the cracking is present at almost all the temperatures, but it is minimal for 1100 and 1200 °C, and it is more pronounced between 1140 and 1160 °C. The crack index plots for all the steels oxidized for 10 min are shown in Fig. 5, and the plots for 30 min are shown in Fig. 6.

Critical temperature is defined as the temperature at which the most cracking occurs. The samples in stage one, oxidized for 10 min, showed a critical temperature for cracking. The maximum critical temperature occurs in Steel 39 between 1140 and 1160 °C, and the critical temperature decreases with the copper content. Also, the maximum value of the crack index decreases with copper content. For the samples oxidized for 30 min, the critical temperature shown by the crack index measurement is consistently found near 1140 °C. The values of the crack index are high only for Steel 39 and Steel 35. For the remaining steels, severe cracking does not occur.

3.2. Stage two results

The critical temperatures for stage two testing were selected from visual observation of the surface photographs of the deformed samples. Table 2 presents the critical temperatures selected as test temperature for stage two testing.

Fig. 7 presents results of Steel 39 deformed at 1150 °C after various oxidation times. In the photographs one can see that the cracking is extensive for oxidation time of 1 min. The cracking decreases and then appears to slightly increase again at 7 min of oxidation. The crack index plot for all the steels (except Steel 09, which exhibited no cracking), are shown in Fig. 8.

For the samples with high copper content, such as Steels 39, 35, 32, and 30, there is a maximum amount of cracking at 1 min. As the copper content decreases, the critical temperature decreases as well, and there is an increase in cracking at longer times. This trend is seen in Steels 32, 30, and 25. For Steels 21 and 20 (those with lower copper content), there is minimal cracking variation for the various oxidation times. Also, the crack index values for stage two tests are significantly lower, as compared to the values determined during stage one tests.

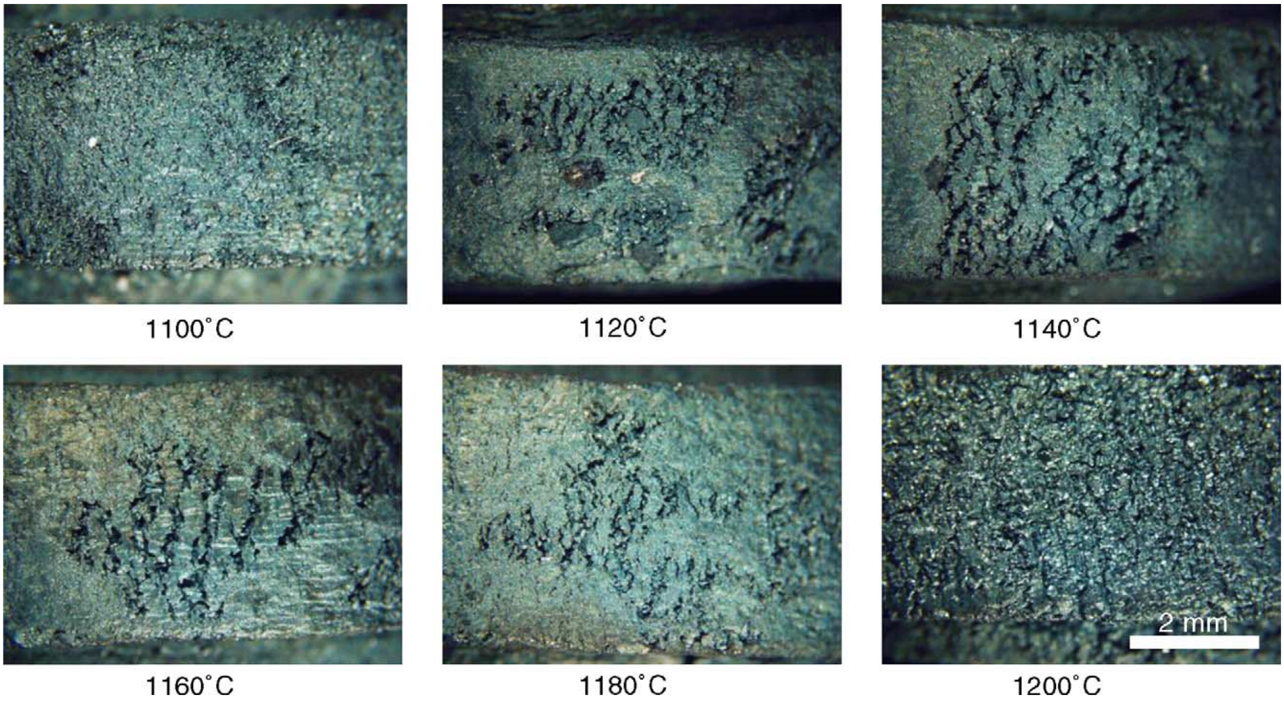


Fig. 4. Steel 39 oxidized for 10 min at different temperatures and deformed.

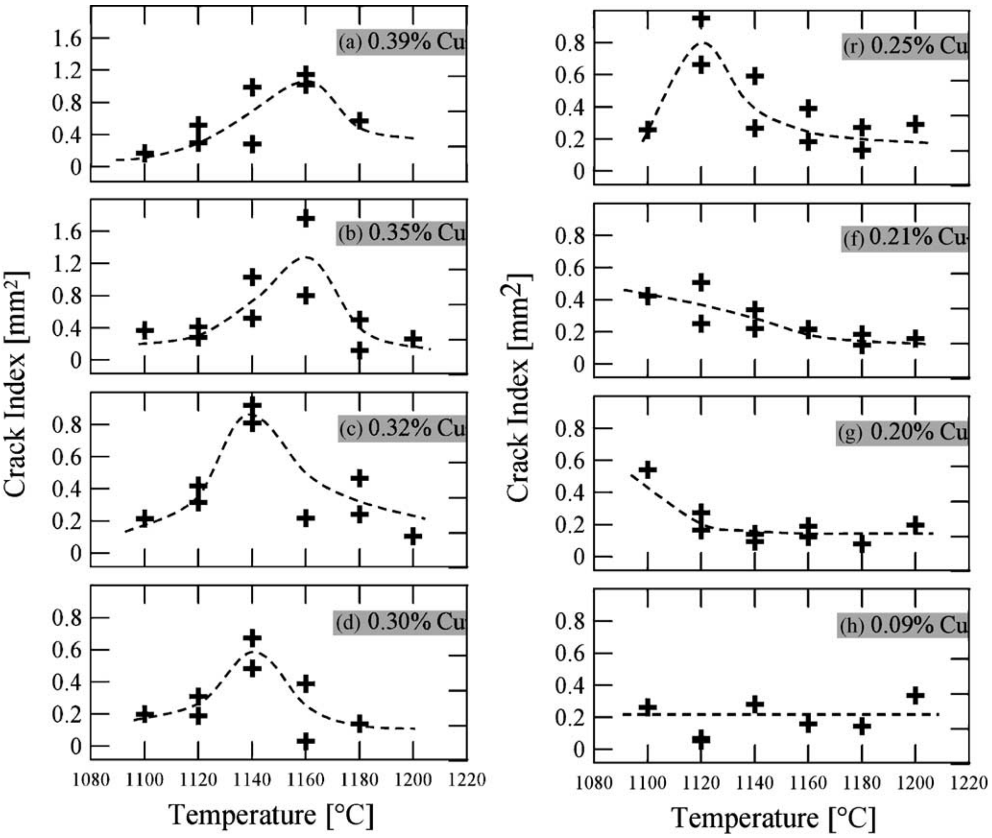


Fig. 5. Crack index measurements for (a) Steel 39, (b) Steel 35, (c) Steel 32, and (d) Steel 30, oxidized for 10 min and deformed. Crack index measurements for (e) Steel 25, (f) Steel 21, (g) Steel 20, and (h) Steel 09, oxidized for 10 min and deformed.

Tables 3 and 4 present a summary of the principal values obtained from the different tests.

3.3. *Oxidation and deformation at 1200 °C*

Steels 39 and 35, those with the highest copper contents, were tested at the highest temperature of the test matrix, 1200 °C. Samples of these steels were oxidized for 1 min and then deformed. The 1200 °C temperature is closer to the actual temperatures that the steel would see in typical forging industry conditions. The oxidation time for the sample size is also fairly realistic. The samples were analyzed to obtain the crack index, and the values are presented in Table 5. This crack index values are as low as the crack index values from Steel 09.

Table 2
Critical temperatures for stage two testing

Steel	Critical temperature (°C)
39	1150
35	1145
32	1135
30	1130
25	1115
21	1115
20	1110
09	1100

4. Discussion

4.1. *Stage one testing*

The samples that were oxidized for 10 min and then deformed produced a variety of crack sizes and distributions for the various steels. The temperature at which cracking

Table 3
Critical temperatures and crack index values from stage one tests

Steel	Oxidized for 10 min		Oxidized for 30 min	
	Critical temperature (°C)	Maximum crack index (mm^2)	Critical temperature (°C)	Maximum crack index (mm^2)
39	1160	1.00	1140	1.80
35	1160	1.20	1140	0.20
32	1140	0.85	1140	0.20
30	1140	0.75	–	0.20
25	1120	0.75	–	0.30
21	1120	0.40	–	0.25
20	1100	0.50	–	0.25
09	1100	0.20	–	0.20

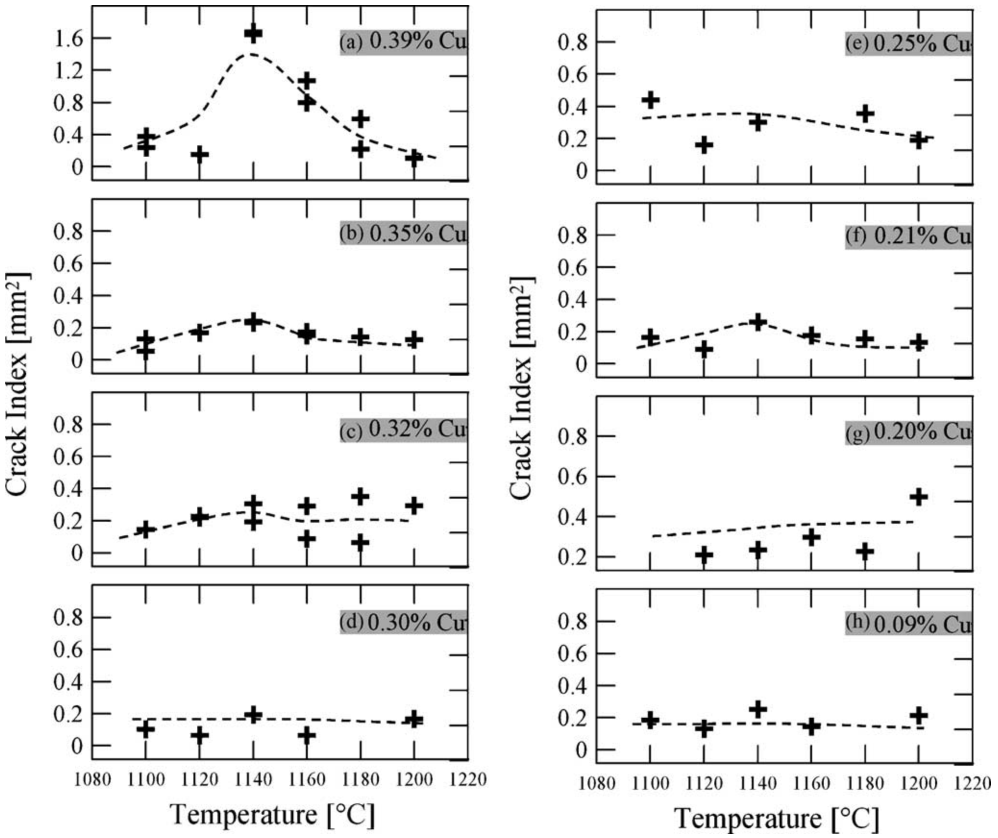


Fig. 6. Crack index measurements for (a) Steel 39, (b) Steel 35, (c) Steel 32, and (d) Steel 30, oxidized for 30 min and deformed. Crack index measurements for (e) Steel 25, (f) Steel 21, (g) Steel 20, and (h) Steel 09, oxidized for 30 min and deformed.

is most significant is called the critical temperature. The most important feature of the critical temperature is that it decreases with decreasing copper content. Fig. 9 shows a graph of the critical temperature as a function of copper content. The crack index also decreases with copper content, as shown in Fig. 10.

The balance between enrichment and dispersion of copper explains the decrease in critical temperature and crack index with decreasing copper content. This is a rational theoretical model that accounts for these maximums.

Copper enrichment at the interface occurs via oxidation of the steel surface; during oxidation copper is rejected by the oxide and diffuses into the steel. The oxidation process is a parabolic function of time; hence, enrichment of copper in the steel is also a parabolic function of time. The oxidation rate is temperature dependent, so the enrichment rate is both temperature dependent and directly dependent on the amount of residual copper. For a given temperature the higher is the amount of residual copper, the higher will be the enrichment. As the temperature increases, both oxidation and enrichment rate also increase.

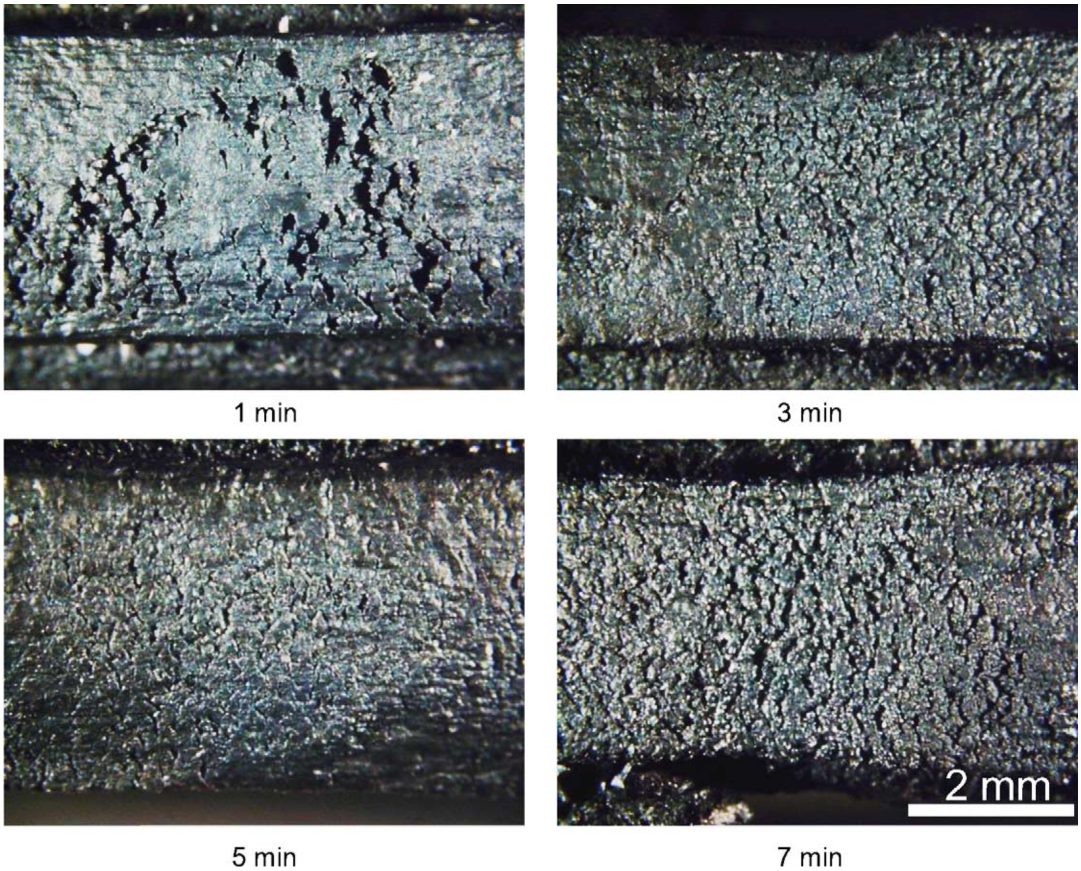
The enrichment process is balanced by the dispersion of copper. The dispersion process occurs via solid-state diffusion of copper in iron. This diffusion involves two competing mechanisms, matrix diffusion and grain boundary penetration. The working temperature where the hot-shortness is significant is the break point of these two mechanisms. Grain boundary penetration predominates up to the point

Table 4
Critical times from stage two tests

Steel	Temperature (°C)	Critical time (min)
39	1150	1
35	1145	1
32	1135	1
30	1130	7
25	1115	7
21	1115	5
20	1110	5
09	1100	–

Table 5
Crack index values for Steel 39 and Steel 35 compared with Steel 09

Steel	Crack index (mm^2)			
	1140 °C for 10 min	1140 °C for 30 min	1110 °C for 1 min	1200 °C for 1 min
09	0.28	0.25	0.010	
39	0.65	1.60		0.015
35	0.75	0.24		0.025



1 min

3 min

5 min

7 min

Fig. 7. Steel 39 oxidized at 1150 °C for different times and deformed.

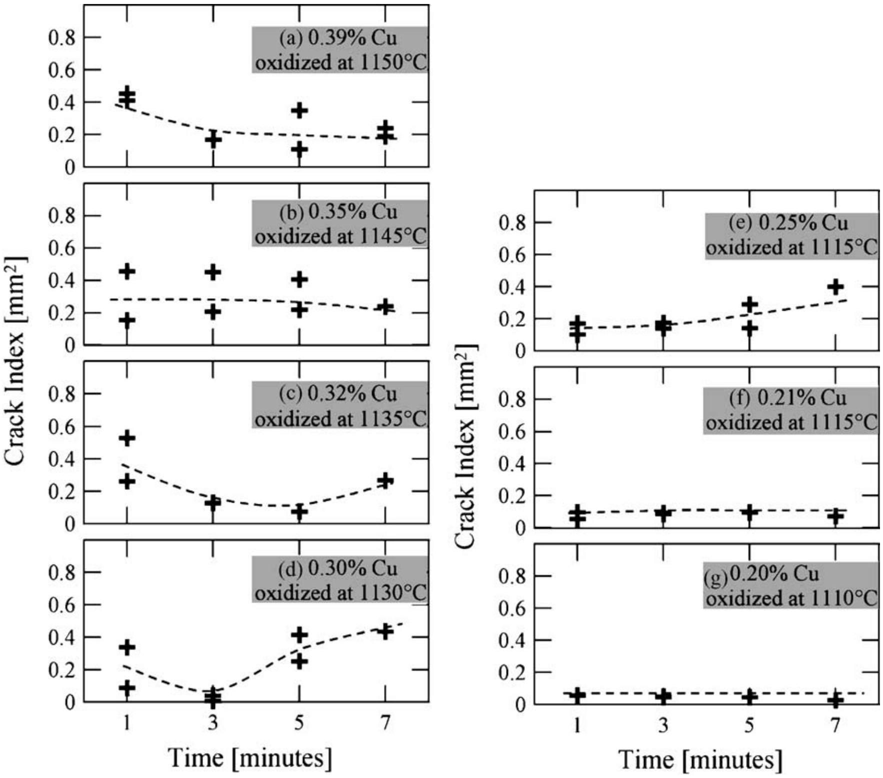


Fig. 8. Crack index measurements for (a) Steel 39, (b) Steel 35, (c) Steel 32, and (d) Steel 30, oxidized at critical temperature for 1, 3, 5, and 7 min and deformed. Crack index measurements for (e) Steel 25, (f) Steel 21, and (g) Steel 20, oxidized at critical temperature for 1, 3, 5, and 7 min and deformed.

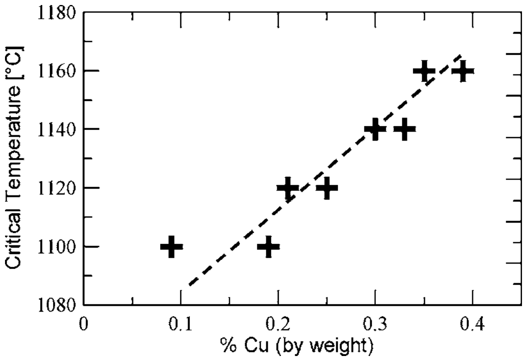


Fig. 9. Critical temperature for cracking as a function of residual copper content.

where the diffusion coefficient is high enough to develop a planar diffusion front, as indicated in [1]:

$$\sqrt{Dt} >> z \tag{1}$$

where D is the diffusion coefficient of copper in iron, t the time, and z the grain boundary thickness. The square root of the product of diffusion coefficient and time starts getting large for diffusivities around the working temperatures and the times from 5 to 10 min. As an example, the diffusion coefficient increases exponentially with temperature: between 1100 and 1200 °C it increases five times.

The enrichment, dispersion and grain boundary penetration are all connected mechanisms that give a temperature window where hot-shortness occurs. Fig. 11 shows a schematic illustration of the competing phenomena as a function of temperature: enrichment, grain boundary penetration, and dispersion (matrix diffusion). The enrichment increases with temperature, and is directly proportional to the amount of residual copper. The grain boundary penetration is an active mechanism, and it is dependent on the enrichment itself. Without a sufficient amount of copper coming from the oxide front, there is no significant copper concentration at the boundaries. As the grain boundary penetration becomes significant, it diminishes with temperature; as the diffusion coefficient increases, it promotes a planar diffusion front. All these mechanisms result in a maximum copper grain boundary concentration that could develop in hot-shortness, dependent on temperature and copper content of the steel. This hypothesis is consistent with the results of the experimentation that showed a maximum in hot-shortness occurrence at a certain temperature and copper content.

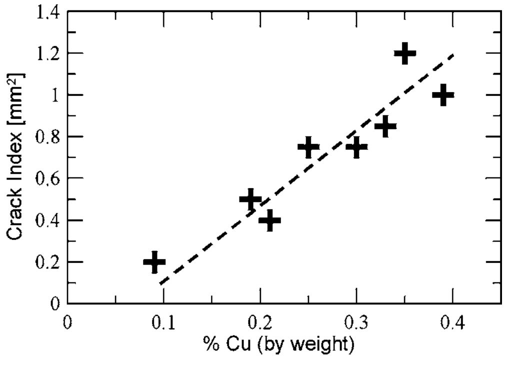


Fig. 10. Maximum crack index as a function of residual copper content.

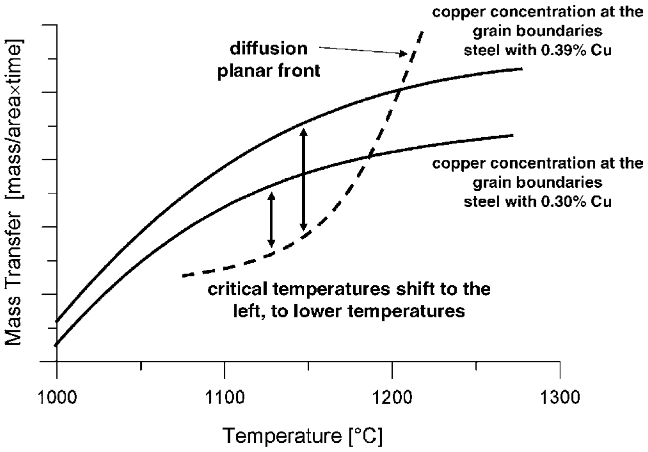


Fig. 11. Schematic illustrating the competition between enrichment and dispersion of copper in grain boundaries near the surface of the specimen.

The size of the cracks observed in photographs and the crack index measurements for the samples oxidized for 10 min are much larger than at any other times. The exception was Steel 39, in which the maximum cracking occurred after oxidation for 30 min at 1140 °C. A 10 min oxidation was able to produce enrichment zones sufficient to cause cracking in most of the steels at different temperatures of the test matrix.

The samples oxidized for 30 min did not exhibit a variation in the critical temperature. Steels 39, 35, and 32 all showed maximum cracking at 1140 °C. The critical temperature of 1140 °C agrees with the temperatures published in the literature [3–5,12,13]. The other five steels did not have significant cracking, and therefore did not have a critical temperature. These results indicate that all the steels at this longer time have achieved a steady state. The amount of copper rejected by the oxide and the dispersion of the copper into the metal is at a steady state. The steady state condition also contributes to the fact that the crack index values are not high.

For Steel 39, the maximum crack index value was found at oxidizing time of 30 min; whereas all the other steels had greater crack index values after oxidizing at 10 min. One of the differences of Steel 39 as compared to the other steels in the test matrix, besides having the highest copper content, is that it has a Cu/Ni ratio which almost reaches a value of 4. For this Cu/Ni ratio, the solidus line from the copper–nickel binary phase diagram is approximately 1160 °C. The critical temperature for this steel in the samples oxidized at 10 min is closer to the solidus line of the system. This observation is an indication that Steel 39 may behave differently than the others. Fig. 12 presents the critical temperature of the steel oxidized for 10 min as a function of the copper to nickel ratio, and the solidus line from the binary Cu–Ni phase dia-

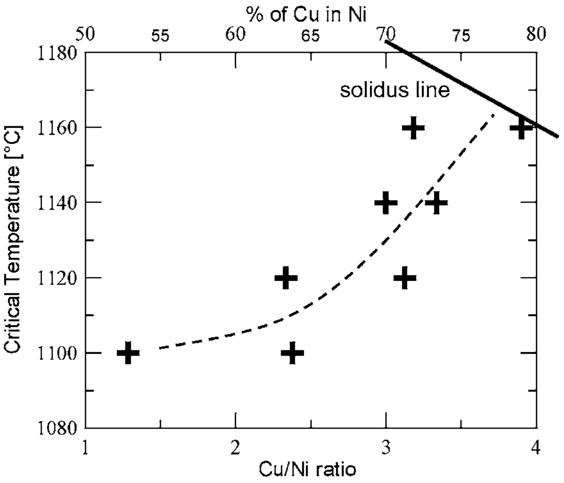


Fig. 12. Critical temperature for samples oxidized for 10 min and the solidus line of the Cu–Ni binary system.

gram. Fig. 12 does not explain why there is a shift in critical temperature when oxidization for Steel 39 increases from 10 to 30 min. However, it does provide a reason why Steel 39 has more severe cracking, regardless of the oxidation time, as compared to the other seven steels in the study.

4.2. Stage two testing

During stage two testing, the primary parameter investigated was oxidation time before deformation. The deformation temperature for each steel was chosen to be the critical temperature as determined by stage one testing (see Table 2). None of the eight steels exhibited severe cracking after deformation. The crack index maximums during the stage two testing series did not exceed a value of 0.5 mm^2, which represents a moderate amount cracking. The surfaces exhibit very small cracks as compared with the specimens from stage one.

One of the more peculiar results during stage two testing is the critical oxidation time and the variation of this critical time with copper content in the steel. For Steels 39, 35, and 32, the maximum cracking occurs with an oxidation time of 1 min. Steels 30 and 25 show maximum cracking occurring at an oxidation time of 7 min, rather than 1 min. Steel 32 has a maximum in the cracking index at 1 min, then the crack index value falls to a minimum at 5 min, and rises again at 7 min. Likewise, Steel 30 starts with high cracking at 1 min, falls to a minimum at 3 min, and rises at 5 and 7 min. In contrast, Steel 25 starts at a minimum crack index value at 1 min, which continues rising with time. All these three steels (32, 30 and 25) exhibit a crack index variation with time. If this index is extrapolated to 10 min of oxidation, it yields a crack index value that is equivalent to one found during stage one testing, in which the oxidation time was 10 min, as shown in Fig. 13.

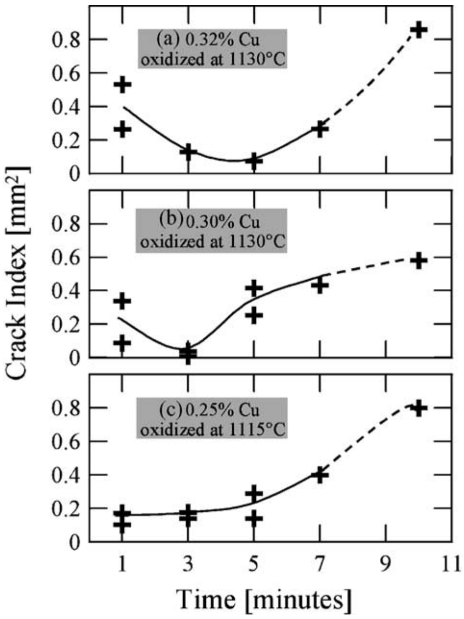


Fig. 13. Extrapolation of the crack index measurements for (a) Steel 32, (b) Steel 30 and (c) Steel 25.

For Steels 39 and 35, extrapolation of the stage two data to 10 min is more difficult to rationalize, since they do not reach the same values as was found during the stage one testing at 10 min as shown in Fig. 14.

It is difficult to provide a full explanation for all these observations. It should be noted that there are several parameters changing when stage one data are compared with stage two data. The copper content varies among the steels, which leads to variations in the enrichment rates. The testing temperature is not the same for all the steels during stage two testing, but is at the temperature associate with the maximum amount of cracking found during stage one. The variation in temperature affects the diffusivity of copper in steel, and thus affects the dispersion rates. The experimental oxidation method is somewhat different between the two stages of testing. Nevertheless, there are two possible explanations or interpretations of the observed data. One is that for steels with

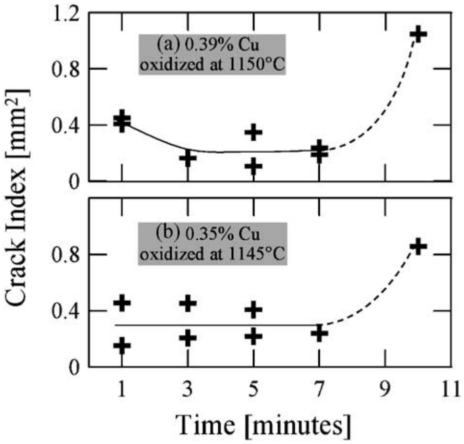


Fig. 14. Extrapolation of crack index measurements for (a) Steel 39 and (b) Steel 35.

significant copper residual content, there are two critical oxidation times. The first is soon after the oxide layer forms, due to the abrupt enrichment from oxidation and rapid penetration into the grain boundaries. Subsequently, the dispersion process accommodates the excess of copper along the grain boundaries evolving into a steady state situation. This would explain the behavior seen in Steels 39, 35, and 32. Steels 30 and 25 do not receive sufficient enrichment to wet the boundaries during the early oxidation times. Even when the oxide layer is growing, and enrichment is occurring, the temperature at which the test is being conducted is lower, causing the diffusion to be reduced. The low temperature and the smaller amount of copper available can delay penetration into the grain boundaries. These two effects, both a slow enrichment and slow dispersion (due to slow diffusion), could explain the maximum cracking being delayed to longer oxidation times. The second explanation is that there is some other process, such as internal oxidation, occurring at the same time. More experiments and analysis would be needed to prove the occurrence of a competing process.

4.3. Industrial insights

One of the main industrial objectives of the present project was to evaluate the newer processing conditions used in modern forge shops that might allow the use of higher copper residual contents to be used for forging without the fear of major surface cracking. As such, special tests were run using Steels 39 and 35. The steels oxidized for 1 min and deformed at 1200 °C. They did not exhibit any cracking. The roughness of the surface of these samples were comparable to the roughness found in the steels with very low copper content, such as Steel 09. It is believed that at such high temperatures the dispersion rate is much higher than the enrichment rate, and the high diffusivity promotes a planar penetration front not allowing grain boundary accumulations; hence, not wetting the grain boundaries. These two results are very encouraging, since the real working temperatures for forging of 1045 steel are around 1260 °C. At industrial forging temperatures, the dispersion should be even higher.

If the working temperature drops below 1200 °C, and the copper content is as high as Steel 39, hot-shortness could occur. It has been proven that for steels with high copper residual content, there is a critical temperature at which surface cracking is a maximum. If the deformation temperature is below the critical temperature or above the critical temperature, the cracking due to hot-shortness will be less.

One recommendation, which has been advocated over the years to prevent or eliminate hot-shortness, is the addition of nickel into the steel to "cover" for the copper residual content. It has not been the focus of extensive discussion in the present study, because the nickel contents of the steels evaluated in the present study are relatively the same (see Table 1). It should not be inferred from the present work that nickel content is unimportant. Steel 39 is a prime example, since it has the highest Cu/Ni ratio of the steels studied; the effects of the nickel as a crack suppressor would be the least in this steel. Steel 39 exhibited the greatest amount of cracking at its critical temperature, which is consistent with the beneficial effects of nickel on copper residual cracking.

5. Summary

By deforming steel specimens at high temperature after varying oxidation times, forging was simulated, with the intention of investigating hot-shortness due to residual copper. The results from the testing performed throughout the project showed that hot-shortness is the result of two competing processes: oxidation rate causing copper enrichment along the grain boundaries, and diffusion causing dispersion of copper from the grain boundaries.

Several plain carbon 1045 steels with copper residual contents from 0.09 to 0.39% (by weight) were tested under different conditions. First, the steels were oxidized and subsequently deformed at different temperatures, for oxidation times of 10 and 30 min. Secondly, the steels were oxidized for different periods of time at their critical temperature, in an attempt to understand the kinetics of the phenomena.

The steels oxidized for 10 min and then deformed exhibited a critical temperature at which the cracking was most severe. As the residual copper content decreased, the critical temperature decreased as well as the amount of cracking in the steel decreased. The steels oxidized for 30 min and subsequently deformed did not show a significant variation in cracking with temperature. The temperature at which the cracking became critical was 1140 °C for all the steels that exhibited a maximum point. The constant critical temperature suggests that the oxidation treatment of 30 min was sufficient to create a steady-state situation for the rates of enrichment and dispersion of copper along the surface grain boundaries, irrespective of copper content.

Results from the time variation testing (stage two) showed that the steels with higher copper content had a maximum amount of cracking at short oxidation times; whereas, for steels with medium copper content, the point of maximum cracking occurred at longer oxidation times. The steels with lower copper content did not exhibit severe cracking for any of the oxidation times tested. It should be noted that the critical temperature decreases with copper content, and the enrichment rate is directly related to the copper content of the steel. At the lower temperatures, the dispersion process is less rapid due to slower diffusion of copper into the steel.

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