The Effects of Strain Rate on the Deformation Behavior of High Strength IF and Bake-Hardenable Sheet Steels for Automotive Applications

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Abstract

The effects of strain rate on the deformation behavior of high strength bake hardenable (BH) and interstitial free (IF) steels were evaluated on samples in the as-received condition and after a laboratory bake-hardening treatment (2% prestrain in tension followed by baking for 30 minutes at 177 ^{o}C). Tension tests were conducted at strain rates ranging from quasi-static to 200 s^{-1}. At quasi-static strain rates, the prestrained and baked BH material exhibited an appreciable increase in yield strength, consistent with anticipated bake hardening response for the alloy. With an increase in strain rate, however, the effects of bake hardening diminished; at the highest strain rate the baked material had approximately the same mechanical properties as observed in the as-received material, prior to the laboratory bake-hardening treatment.

Introduction

A continuous trend in the automotive industry is the use of higher strength sheet steels to decrease car weight and increase crashworthiness. Interstitial free and bake hardenable steels are used primarily for desirable formability and or dent-resistance, respectively [1]. Bake hardenable steels are designed to have a small amount of interstitial carbon or nitrogen in solution and are advantageous due to an increase in yield strength following sheet forming and paint baking. This increase in yield strength is due to interstitial solute-dislocation interactions. Baking of prestrained material allows the interstitial solute atoms to diffuse to the existing dislocations, forming Cottrell atmospheres, which prevent existing dislocation movement. It is believed [2] that new dislocations must be generated to cause plastic strain. The applied stress must increase to generate and propagate new dislocations, and results in the observed increase in yield strength in bake hardenable steels.

With the increased application of bake hardenable steels in the automotive industry and the emphasis on predicting material behavior during a crash where strain rates may exceed 100 s^{-1} [3], it is important to understand the mechanical behavior of BH steels over all strain rates anticipated in a crash situation. To date the primary data available on BH steels were obtained at quasi-static strain rates on samples prestrained in tension a fixed amount of strain (e.g. 2 pct) and subjected to paint bake simulation (typically 20 min. at 170 ^{o}C) [4]. The magnitude of the strength increase due to strain aging depends sensitively on the strain history prior to aging. A maximum in the strength increase after aging occurs in uniaxially prestrained samples tested parallel to the (original) prestrain direction [5]. Significant variations in the response to aging occur when there is a change in orientation between the samples tested before and after aging, and the magnitude of the apparent strength increase due to aging can vary from the maximum value to essentially zero [5,6]. The effect of strain path on aging behavior has been related to differences in the stress required to operate the appropriate slip systems. That is, a change in orientation after prestraining and aging is likely to require activation of new slip systems during subsequent deformation, and pinning of the dislocations generated during the prestrain on the initial slip system is less likely to influence the flow stress on the new slip system.

Previous studies on the effects of strain rate on the mechanical properties of iron and low carbon steels have shown that the flow stress increases with an increase in strain rate or decrease in temperature producing distinct regions of strain rate and temperature dependence [7]. At low strain rates and high temperatures flow is controlled by long-range friction stresses that cannot be overcome by thermal vibration assistance. This athermal stress increases with alloy content. At higher strain rates and low temperatures, flow is controlled by short-range barriers such as Peierls barriers. Thermal vibrations are able to assist in overcoming these barriers, and flow becomes sensitive to strain rate and temperature. However, to date limited systematic studies have been performed to evaluate the combined effects of solid solution strengthening due to interstititial redistribution during aging and strain rate on the mechanical properties of low carbon steels. In this study, the strain rate dependence of a stabilized IF steel are compared to similar results on a bake hardening steel, both in the as-received condition and after a prestrain and aging treatment to assess the interrelationships between strength increases due to work hardening, solute pinning, and strain rate hardening.

Experimental Procedure

Material

The steels used for this study were aluminum killed interstitial free and bake-hardenable steels. The chemical compositions for each steel are listed in Table I. The main difference between the steels is the additional amounts of aluminum and niobium in the IF steel. These additions ensure that all carbon and nitrogen will be precipitated out of solution in the IF steel. It is also important to note the addition of phosphorus in both steels. The addition of phosphorus enables solid solution strengthening with only minor effects on bake hardenability [8]. The steels were commercially produced and received in approximately 1.4 mm thick sheets.

Table I Chemical Composition of Steels used in Study, Weight Percent

Steel	C	P	Mn	Nb	Al	N
IF	0.009	0.064	0.24	0.025	0.050	N/A
BH	0.008	0.078	0.32	0.005	0.022	N/A

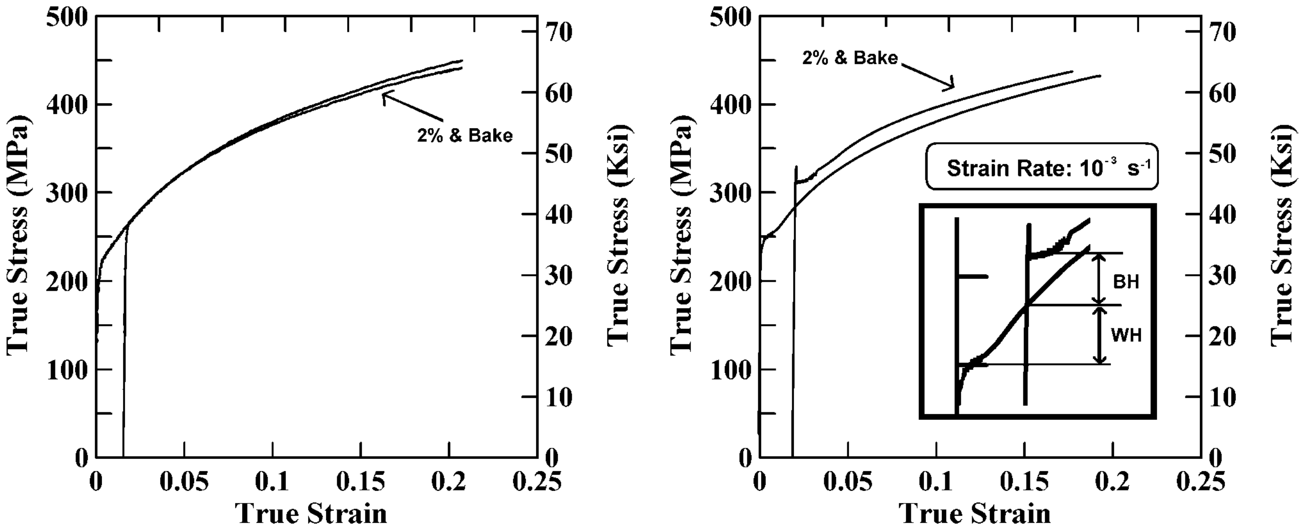
Laboratory Tensile Testing

Laboratory tensile tests were conducted on both steels over a wide range of strain rates, from 10^{-3} to 200 s^{-1}. Both steels were tested in the as-received condition, and after a prestrain and bake treatment (samples were prestrained in tension at a quasi-static rate, followed by a 30 minute aging at 177 ^{o}C). Longitudinal tensile samples with a 25.4 mm reduced gauge length were machined with the as-received thickness. Low strain rate tests were conducted using a conventional servo-hydraulic tensile testing frame. Tensile tests at rates 10^{-1} s^{-1} and higher were conducted using a commercial high strain rate servo-hydraulic testing system. Strain measurements were made using high elongation strain gauges mounted directly on the gauge section of each sample. Load was measured both with a piezoelectric load washer, and with an elastic strain gauge mounted on the grip section of the sample. A detailed description of these test methods is summarized elsewhere [3,9].

Results and Discussion

Quasi-Static Mechanical Properties

The quasi-static (10-3 s-1) tensile properties for each test condition are shown in Figure 1. In each Figure, the curve for the prestrained steel sample is offset a strain of 0.02. The mechanical properties of the prestrained and baked IF steel strongly match the properties of the as-received material. The yield strength of the prestrained and baked sample increased only by the work hardening increment of the as-received material during prestraining. This behavior was expected of the stabilized IF steel, and quasi-static tests found the increase in strength due to work hardening to be approximately 28 MPa for 2 pct. prestrain. The plot in Figure 1b for the bake hardenable steel shows a distinct increase in yield strength after prestrain and baking. This increase in yield strength can be divided into two contributions 1) work hardening and 2) bake hardenability. The bake hardenability contribution can be found by subtracting the flow stress after 2 pct. prestrain from the lower yield strength after baking, as seen in the inset in Figure 1b [10]. This value (i.e. BH) was determined to be 47 MPa at quasi-static strain rates, and the work hardening contribution was found to be 26 MPa.

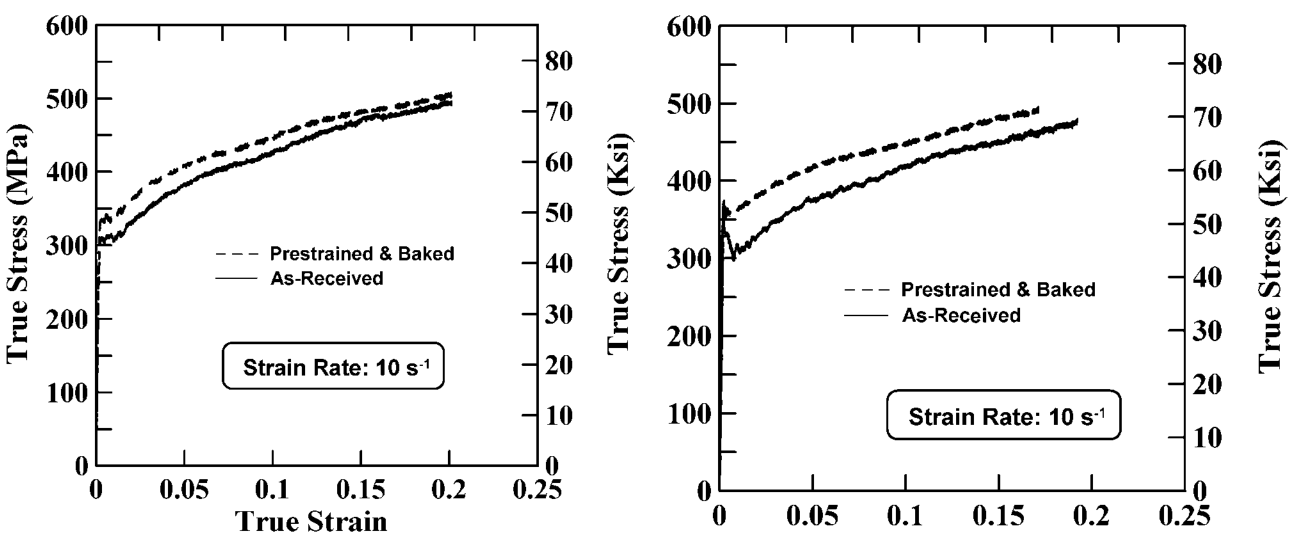


a) b)

Figure 1: Quasi-static true stress-strain curves for a) the IF steel in both the as-received condition and the prestrained and baked condition, and b) the BH steel in both conditions. The inlay demonstrates the measurement of WH and bake hardenability.

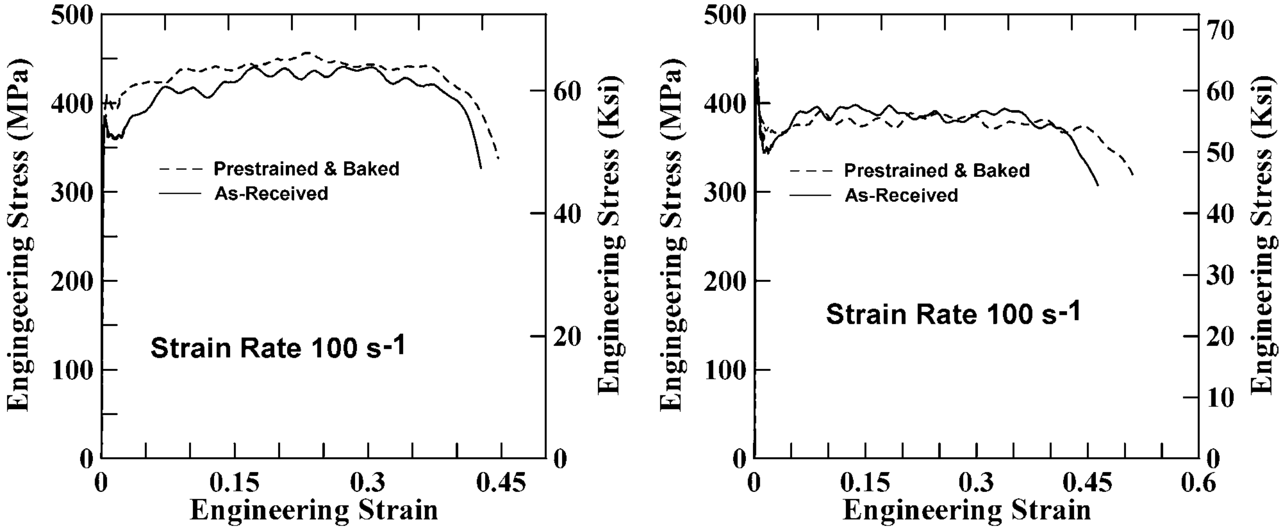
High Rate Mechanical Properties

Flow curves for both steels in each condition, tested at the higher rate of 10 $s^{-1}$are shown in Figure 2. Comparing Figures 1 and 2, there are noticeable differences between the curves at 10^{-3} s^{-1} and 10 s^{-1}. Both the yield strength and tensile strength increase with strain rate. One important observation is that the work hardening rate is lower at the higher strain rate. This effect is even more pronounced at a strain rate of 100 s^{-1}, as seen in Figure 3. It should be noted that the curves at 100 s^{-1} were plotted as engineering values, because the work hardening rate is so low that it became difficult to identify when non-uniform elongation (necking) began. The next section considers the effect of strain rate on the yield strength of the steels analyzed.



a) b)

Figure 2: True stress-strain curves for a) the IF steel and b) the BH steel tested at a strain rate of 10 s^{-1}.



a) b)

Figure 3: Engineering stress-strain curves for a) the IF steel and b) the BH steel tested at a strain rate of 100 s^{-1}.

There are several methods of calculating and plotting strain rate sensitivity values [9]. The method used in the present study is a semi-logarithmic relationship as shown in Equation 1.

$$\beta = \frac{\partial \sigma}{\partial (\log \dot{\varepsilon})} \tag{1}$$

Where σ= flow stress, $\dot{\varepsilon}$ = strain rate, and β= the semi-logarithmic strain rate sensitivity coefficient. A mechanical property, in this case yield strength, is plotted as the function of the log of strain rate and the slope of this line is commonly referred to as the β value. A high β value correlates to a high strain rate sensitivity.

Figure 4 displays the yield strength for each IF steel test condition for the IF steel plotted as a function of strain rate. In this figure, yield strength is taken as the 0.2 % offset yield strength for samples that do not exhibit a yield point and lower yield strength, and the lower yield strength for samples that exhibit a yield point. There are many important strain rate effects shown in Figure 4. Firstly, for all test conditions, the yield strength increased with strain rate. The strain rate sensitivity of the yield strength also increased with strain rate. This phenomenon is better seen by examining Figure 5, which plots β for the lower yield strength as a function of strain rate. As shown, the sensitivity to strain rate in the IF steel is insensitive to the aging treatment. These results are consistent with several prior studies [11,12,13].

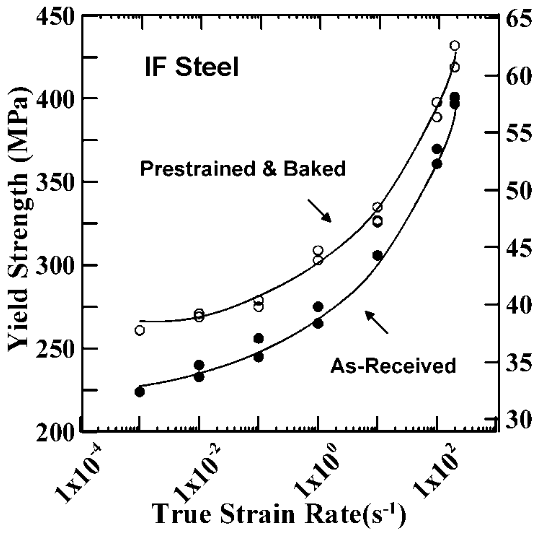


Figure 4: Yield strength values of the IF steel as a function of strain rate.

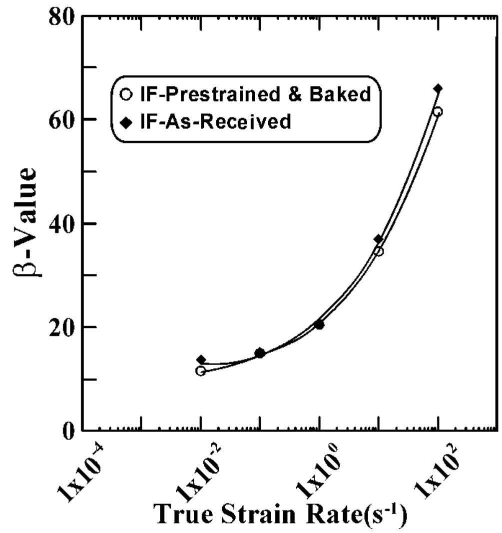


Figure 5: β values for yield strength of the IF steel, plotted as a function of strain rate.

From Figure 4, the strength increase after prestraining and aging for the IF steel remained approximately constant at all strain rates, at 28 MPa in comparison to the yield strengths of the as-received condition at all strain rates. This implies that the increase in dislocation density associated with prestrain had no effect on the strain rate sensitivity of the material. Bruce [9] also observed that prestrain in an IF steel did not alter the strain rate dependence of the flow stress. She suggested that cold work introduces long-range obstacles to dislocation movement, and contributions of these obstacles to flow stress are independent of temperature or strain rate. This suggestion has been confirmed by several other studies [9,11,12].

Figure 6 displays the lower yield strength of each test condition for the BH steel plotted as a function of strain rate. The results were similar to the results of the IF steel in that 1) the yield strength for each condition increased with strain rate and 2) the sensitivity of the yield strength increased with strain rate. However, there was one distinct difference in the behavior of the BH and IF steels. The strain rate sensitivity of the prestrained and baked BH steel was less than the as-received condition. Figure 7 is a plot of β values for yield strength for the BH steel. It clearly shows that for all rates studied the prestrained and baked condition was less sensitive to strain rate.

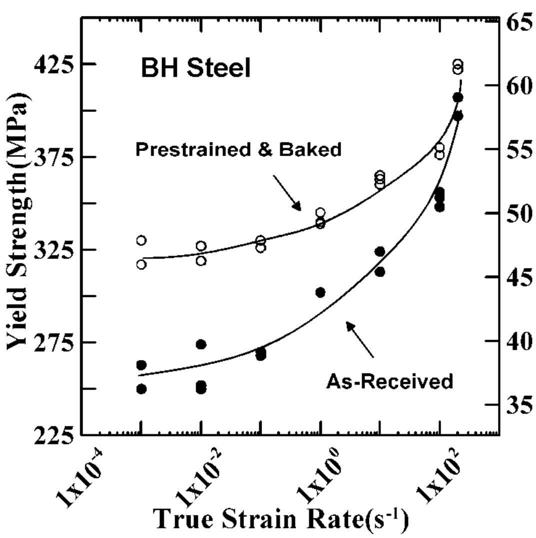


Figure 6: Yield strength values of the BH steel as a function of strain rate.

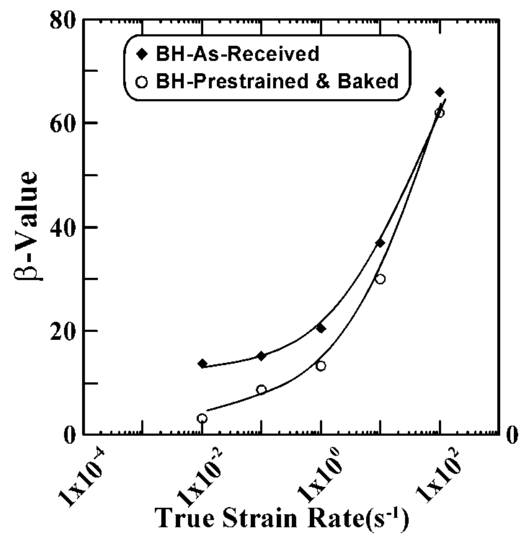


Figure 7: β values for yield strength of the BH steel, plotted as a function of strain rate.

At quasi-static rates, the yield strength increased by approximately 70 MPa, while at a rate of 200 s^{-1} the difference was only approximately 23 MPa. Assuming that the work hardening contribution to the yield strength was independent of strain rate, by the same reasoning used in analysis the IF steel, this implies that the contribution of bake hardenability decreased with strain rate.

Figure 8 compares the effects of strain rate on the strength increase after prestrain and aging for the IF and BH steels. At each strain, this figure plots the difference between the yield strength after prestrain and baking and the yield strength of the as-received materials presented in Figures 4 and 6. As shown, the strength increase for the IF steel remains essentially constant at about 28 MPa, while the strength increase for the BH steel decreases from abut 70 MPa at quasi-static strain rate to essentially the same value as the IF steel at high strain rates. At each strain rate the difference in the two curves shown in Figure 8 is the bake hardening increment, which decreases from approximately 47 MPa at low strain rates to essentially zero at high strain rates.

Three major observations from these data on the response to bake hardening are: (a) at quasi-static strain rates, there is a significant increase in strength due to aging and a return of a well defined yield point on loading; (b) the strain rate sensitivity of the baked materials at the lower strain rates is much lower than the as received, unbaked material; and (c) the contribution of bake hardening decreases with an increase in strain rate. These observations can be rationalized by noting that the stress required to move dislocations in iron is comprised of thermal and thermal components. For pure iron discussed previously, and for the IF steel and the un-aged material discussed here, the strain rate dependencies shown in Figure 5 and 7 are almost identical. The increase in the dependency of strength with strain rate suggests that there is an increase in the contribution of thermally activated dislocation processes, e.g. the formation of double-kink pairs, as dislocations move past Peierls barriers, to the overall stress required for dislocation movement (14) such that at high strain rates the properties are dominated by the stress for individual dislocation movement. In contrast, for the prestrained and baked BH steel at the lower strain rates, the high strengths and low sensitivity of strength to strain rate suggests that the mechanisms responsible for strengthening are different. If it is assumed that the process of aging produces a fully pinned dislocation structure, then on reloading the stress for deformation corresponds primarily to the stress to generate sufficient new dislocations as controlled by the long range stress fields associated with the dislocation structure and the stress required to operate dislocation sources. In this strain rate regime, the flow stress would exhibit a low and mild dependency on strain rate, as observed. However, with an increase in strain rate the inherent resistance to the movement of individual dislocations by the same processes operating for the unaged material dominate, and the effects of pinning due to aging are overshadowed by the inherent processes of dislocation movement over short range barriers, such as Peierls barriers. Therefore, all materials in this study exhibit equivalent flow stresses and strain rate sensitivities at the high strain rates. Similar effects of solute additions were observed by Bruce [9] in her study of the effects of P additions to IF steels. She showed that the strength increase due to P at low strain rates disappeared with an increase in strain rate in a manner analogous to the behavior observed here for interstitial effects in the baked material.

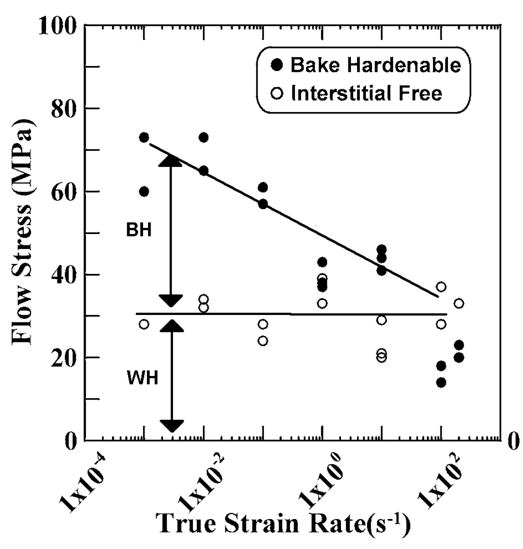


Figure 8: Difference between the lower yield strength of the prestrained and baked condition and the as received condition as a function of strain rate for the two steels studies

Conclusions

1. For all materials in the as-received or prestrained and aged condition, the flow stress increased with strain rate consistent with previous results on low carbon steels.

2. The strain rate sensitivities, β, of both materials in the as–received condition, as well as the IF steel in the baked condition were equivalent and increased with strain rate. The increase of strain rate sensitivity with strain rate reflected the effects of thermally activated dislocation motion.

3. After prestrain and aging the strength of the BH steel increased. The magnitude of the BH increment was a strong function of strain rate, decreasing from approximately 47 MPa at quasi-static strain rates to approximately zero at high strain rates.

4. At the lower strain rates, the strain rate sensitivity of the prestrained and baked BH steel was significantly lower than for the other materials. The lower dependency of strength on strain rate suggested that dislocation motion at low rates is controlled by athermal processes. However, at the higher strain rates all materials exhibited similar dependencies on strain rate and correspondingly similar stress requirements for dislocation motion, which were independent of the effects of solute redistribution on aging.

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