The Effect of Warm Prestressing on Notch Fracture Strength

The effect of warm prestressing at various stress levels on the notch bend fracture properties of a Ni-Mo-V steel at two levels of strength and Charpy FATT is determined. Warm prestressing of a notch sensitive steel effected increases in notch fracture strengths up to 150 percent of the unprestressed value. The fracture strength after prestressing increases proportionately with prestress level. The results indicate that the efficacy of warm prestressing is dependent on the temperature at which the notch strength is determined and its relation to the notch strength versus temperature behavior for a material.

Introduction

The profound influence of temperature on the notch properties and especially on the notch strength of plain carbon and ferritic alloy steels is well known. The general behavior is that the notch strength can be markedly decreased as the test temperature is lowered; the temperature range in which this occurs is referred to as the transition temperature range and the general phenomenon is the ductile-brittle fracture transition.

One means by which the notch strengths at temperatures within and below the transition range can be altered is by warm prestressing. This is done by loading at a temperature above the transition range to some stress level below the notch fracture strength at this higher temperature, then unloading, cooling to and testing at some lower temperature. Several investigators, notably Srawley and Beaucham [1] and Steigerwald [2], have shown the beneficial effects imparted by the warm prestressing treatment. In both instances, the materials investigated were steels heat-treated to very high strength levels and the tests were made on relatively thin sheet-type specimens.

In this paper, the results of an investigation into the effects of warm prestressing for a steel heat-treated to intermediate strength levels (approximately 120,000 to 130,000 psi ultimate tensile strength) and tested as notch specimens of relatively large cross sections are reported. Points of similarity of the test results to previous work on higher strength steels are noted and some of the material and test specimen geometry conditions which need to be considered in determining the general efficacy of warm prestressing are discussed.

Experimental Procedures

Material and Specimens. The material was from a 4Vs-in. square reforged bar of a consumable-electrode melted Ni-Mo-V steel of the following composition (weight percent):

Ni  Mo  V  O  Mn  Si  P  S
2.6  0.44  0.09  0.30  0.48  0.22  0.03  0.03

The alloy was heat-treated to two conditions. These and the resulting mechanical properties are shown below:

<table>
<thead>
<tr>
<th>Condition</th>
<th>Ultimate tensile strength, ksi</th>
<th>0.2% yield strength, ksi</th>
<th>Elong., in. percent</th>
</tr>
</thead>
<tbody>
<tr>
<td>1525 F - 6 hr AC</td>
<td>119.4</td>
<td>97.9</td>
<td>23</td>
</tr>
<tr>
<td>1075 F - 16 hr + 1125 F - 16 hr AC</td>
<td>108.2</td>
<td>20</td>
<td></td>
</tr>
<tr>
<td>1600 F - 6 hr AC</td>
<td>130.5</td>
<td>108.2</td>
<td>20</td>
</tr>
<tr>
<td>1075 F - 16 hr + 1125 F - 16 hr AC</td>
<td>108.2</td>
<td>20</td>
<td></td>
</tr>
</tbody>
</table>

The test specimens were two inches square in cross section by nine inches long with a 45 deg included angle, 20 percent deep machined notch terminating in a fatigue crack 0.015-0.060 in.

Test Procedures

The general test procedure followed was that of determination of the notch bend strength of fatigue-cracked bars at a subtransition temperature before and after warm prestressing at various nominal stress levels. The specimens were supported as a simple beam and loaded opposite the notch (three-point loading) at a testing speed of about 0.025 in/minute. For tests below ambient temperature, the specimens were placed in a coolant bath of alcohol and dry ice. Heating cabinets were used for tests above ambient temperature. For both cases, the specimen temperatures were determined by thermocouples peened into a location near the notch.

As described above, the prestress and maximum bending loads are reported as a nominal bend stress calculated from simple beam theory, i.e.,

\[
\sigma_{NBS} = \frac{1.5PL}{bh^2}
\]

where

\[
\sigma_{NBS} \quad \text{notch bending stress}
\]

\[
P \quad \text{maximum load}
\]

\[
L \quad \text{bending span}
\]

\[
b \quad \text{specimen width}
\]

\[
h \quad \text{depth below notch}
\]

Test Results

The effect of temperature on the notch bend strength of the
Fig. 1 Effect of temperature and pre-stressing on the notch bend strength of a Ni-Mo-V steel (FATT = 150°F)

Fig. 2 Effect of temperature and warm prestressing on the notch bend strength of a Ni-Mo-V steel (FATT = 215°F)

Fig. 3 Effect of warm prestressing on the sub-transition notch fracture strength of a Ni-Mo-V steel
fatigue cracked bars prior to warm prestressing is shown in Figs. 1 and 2. Comparison of the notch bend fracture properties of the virgin bars in the two conditions of heat-treatment indicate the same general effect. As the test temperature is decreased, the notch bend strength passes through a transition from high-to-low values.

Also, these figures show the warm prestressing conditions and the resultant fracture properties upon subsequent testing at a lower test temperature. The fracture stress of the prestressed bars generally increases proportionately with the level of prior prestressing; this is shown more clearly in Fig. 3. This figure shows that at high prestress levels the notch strength at subtransition temperatures was increased by approximately 150 percent. However, for both material conditions there appears to be an optimum prestress level above which the fracture strength of the prestressed bar becomes less than the prestress level. Examination of those bars prestressed to above the optimum level revealed evidence of cracking during the prestressing cycle. This suggests that the optimum level for prestressing is less than the stress required for crack initiation at the prestress temperature.

The increase in subtransition notch fracture strength of prestressed bars was reflected only in the load at fracture. In all cases the load-deflection curves of prestressed bars were linear to fracture with no indication of gross deformation. This behavior indicates the localized nature of improvement by warm prestressing; only the material near the notch or defect is affected and there is no observable change in gross material properties.

The fracture appearance of the prestressed bars is shown in Fig. 4. At the lowest prestress level used, the fracture appearance is identical to the unprestressed bars tested at subtransition temperatures; the fracture mode is entirely cleavage with no indication of shear lips or fibrous tears near the precracked notch.

Prestress level, 68.6 kpsi; NBS, 78.6 kpsi; 2X
Prestress level, 160.0 kpsi; NBS, 168.0 kpsi
Prestress level, 127.5 kpsi; NBS, 134.0 kpsi; 2X
Prestress level, 220 kpsi; NBS, 181.0 kpsi

Fig. 4 Fracture appearance of prestressed bars of Ni-Mo-V steel (FATT = 150 F) tested at -50 F
The proportionality between prestress level and fracture strength of the material of this study is shown in Fig. 3. A similar relationship derived from many other test results is shown in Fig. 5. Since these data were obtained on a large number of alloys of different strength levels, this figure shows the relationship between prestress level and fracture stress both normalized with respect to the unprestressed fracture strength. It is apparent that, within the rather wide limits of scatter associated with fracture testing the notched fracture strength of a prestressed bar is proportional to the level of prestressing.

**Discussion**

The test results obtained in this study are similar in general features to results reported by previous investigators for other materials and test specimen configurations. This indicates that the improvement in notch fracture strength at some lower temperature by a prestressing procedure applied at a higher temperature is a rather general phenomenon.

Both Srawley and Beauchem [1] and Steigerwald [2] have listed and discussed the possible mechanisms by which warm prestressing can lead to improved notch strength. Restating these mechanisms briefly, they are: (a) production of cold-worked material around the crack notch tip; (b) "blunting" of notch radius; (c) possible change in crack front from fatigue crack to ductile tear; and (d) creation of compressive residual stresses around crack notch tip. Steigerwald has concluded that the compressive stress mechanism was the most applicable, particularly to those situations where low levels of prestress are used. The present results are explicable by this mechanism. However, it can be pointed out that the "blunting" mechanism could also apply. There may be no physical blunting of the crack notch radius but the plastic deformation induced could make the "effective" radius larger. It would be difficult, if not impossible, to make a clear-cut distinction between these two mechanisms.

Although warm prestressing had a beneficial effect on notch strength in the present and previously cited studies, it should be recognized that there may be cases where the opposite effect may be obtained. Materials, particularly some plain carbon steels, that are susceptible to strain aging may be adversely affected by warm prestressing.

If the residual stress mechanism is the one most applicable, it follows that the sense of the prestressing has to be in the same direction as the subsequent applied load. A corollary to this is that a Prestress of an opposite sense could result in reduced notch fracture strength.

The efficacy of warm prestressing is very dependent on the temperature at which the notch strength is determined and its relation to the unprestressed notch strength versus temperature behavior for a material. For example, with reference to Figs. 1 and 2, consider that the temperature of interest is 75 deg F. For the notch severity and specimen geometry conditions used in these tests, it is evident that warm prestressing would be of little or no benefit for the material heat-treated to the condition of Fig. 1 but would improve the notch strength for the condition of Fig. 2. Since the principal difference in this steel between the two conditions is in their Charpy transition temperatures, it is deduced that for alloy steels of this category, warm prestressing would be of most benefit when the Charpy transition temperature is high relative to the service temperature of the structural component. The need for and the benefits of warm prestressing in such steels can be expected to decrease as the Charpy transition temperature is lowered toward and below the service temperature.

There is a further consideration in assessing the efficacy of warm prestressing. It has been shown previously [4] for an alloy steel similar to that for Figs. 1 and 2 that notch severity and specimen size have a marked effect on the temperature dependence of notch strength. As the severity of the notch and the gross size of specimen are reduced, the temperature range of the transition in notch strength is shifted to lower temperatures and the strength at temperatures below the transition is increased. As a result, the efficacy of warm prestressing for a particular structural member depends on size and severity of the defect present and the geometry of the piece in addition to the inherent characteristic of the material. In particular, it would be expected that the need for and the benefits of warm prestressing would be greatly reduced if a structural component contains only small size defects of mild severity.
The preceding discussion of the material and geometrical factors influencing response to warm prestressing is summarized by the plot shown in Fig. 5. The largest relative benefits of warm prestressing are noted when material and test conditions combine to give low notch fracture strength in the un prestressed state.

Finally, the variations in the texture of the fracture surfaces with various levels of prestressing is of interest in relation to some previous observations made by Barton and Hall [5]. In their tests on the propagation of brittle fractures in wide plate specimens of mild steels, they noted the characteristic chevron pattern in areas where the crack velocity was high but the chevrons were absent and the fracture surface texture was smooth in areas where the crack velocity was relatively low. In their tests, the reduction in crack velocity was due to the presence of compressive residual stress field. In the present study, the textural roughness and presumably the velocity of crack propagation across the specimen increased with increasing notch fracture strength as a result of warm prestressing. It is believed that chevron markings in plate type specimens and high textural roughness in notch bend specimens of more nearly square cross sections are both indicative of the presence of elastic strain energy considerably in excess of that just needed for the propagation of the fracture. Warm prestressing has an effect on the appearance of the subsequent fracture because it increases the applied stress necessary to initiate the fracture which in turn increases the amount of strain energy available during the propagation of the fracture. This further illustrates the localized nature of warm prestressing since the bulk of the material is not altered in respect to the energy requirements during crack propagation.

Conclusions

The experimental results of this investigation indicate that warm prestressing of notch sensitive steels effected increases in notch fracture strength up to 150 percent of the un prestressed value. The prestressed fracture strength increases proportionately with prestress level to an optimum level which is determined by the stress for crack initiation during prestressing. The efficacy of warm prestressing is shown to be dependent on the temperature at which the notch strength is determined and its relation to the un prestressed notch strength versus temperature behavior. The need for and the benefits of warm prestressing can be expected to decrease as the notch sensitivity of a material decreases.

References