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CONSTITUTIVE FLOW RELATIONS FOR AUSTENITIC STEELS DURING STRAIN-INDUCED MARTENSITIC TRANSFORMATION

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Abstract.—Comparison of the plastic flow properties of transforming metastable austenite, stable austenite, and martensite over a range of temperatures and strain rates allows quantitative estimates of (a) the static-hardening effect of the two-phase mixture and (b) the dynamic-softening effect of the transformation as a deformation mechanism. A constitutive relation is derived predicting the flow behavior of metastable austenite from the strain-induced transformation kinetics and the flow properties of the two separate phases.

Introduction.—Recent analyses have demonstrated that theory of martensitic transformation kinetics can predict the flow behavior of metastable austenitic steels in the low-temperature regime where stress-assisted transformation (nucleated at the same sites which trigger the transformation on cooling) controls the plastic flow (1,2). At higher temperatures where strain-induced transformation (nucleated at new sites produced by plastic strain) is dominant, a kinetic model has successfully accounted for the dependence of volume fraction martensite, \( \beta \), on plastic strain, \( \gamma \), over a range of strain states (3,4), but a suitable model does not exist for the prediction of the resulting plastic flow behavior. Analysis of the shape of stress-strain curves obtained under these conditions identifies two major factors controlling the flow stress: (a) a static-hardening effect associated with the two-phase mixture, and (b) a dynamic-softening effect arising from the operation of the martensitic transformation as a deformation mechanism (5,6). The present study was undertaken to quantitatively determine these two contributions to the flow behavior, and to develop a model with which constitutive flow relations for a transforming material can be predicted from knowledge of the \( f(\gamma) \) transformation curves and the flow properties of the two phases.

Materials and Experimental Procedures.—The compositions of the vacuum-melted steels investigated are given in Table I. Steel A is a commercial high-formability metastable austenitic stainless steel. Steel B is a stable austenitic composition derived from steel A by increasing the Cr and Mn contents in such a way as to maintain a constant intrinsic stacking-fault energy according to a thermodynamic model for the fault energy (7). Steel C is a martensitic composition derived from steel A by reducing the Cr content, the element contributing the smallest solution-strengthening effect in martensite. Steels B and C can be reasonably expected to duplicate the flow properties of the austenite and martensite constituents in steel A.

<table>
<thead>
<tr>
<th>Material</th>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>Cr</th>
<th>Mn</th>
<th>Mo</th>
<th>Cu</th>
<th>Al</th>
<th>P</th>
<th>S</th>
</tr>
</thead>
<tbody>
<tr>
<td>Metastable Austenite</td>
<td>0.12</td>
<td>0.47</td>
<td>1.03</td>
<td>14.17</td>
<td>7.22</td>
<td>0.55</td>
<td>1.95</td>
<td>0.017</td>
<td>0.020</td>
<td>0.010</td>
</tr>
<tr>
<td>Stable Austenite</td>
<td>0.11</td>
<td>0.46</td>
<td>4.77</td>
<td>17.60</td>
<td>6.97</td>
<td>0.55</td>
<td>1.83</td>
<td>0.020</td>
<td>0.020</td>
<td>0.012</td>
</tr>
<tr>
<td>Martensite</td>
<td>0.11</td>
<td>0.45</td>
<td>1.04</td>
<td>6.87</td>
<td>7.03</td>
<td>0.57</td>
<td>1.88</td>
<td>0.035</td>
<td>0.021</td>
<td>0.012</td>
</tr>
</tbody>
</table>

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The steels were obtained as cold-rolled sheet in thicknesses of 0.7 mm (A) and 1.0 mm (B and C). Flat tensile specimens were machined with gauge sections 0.250 in. (6.35 mm) in width and 1.50 in. (38.1 mm) in length. Vacuum encapsulated specimens were solution-treated for 5 min. at 1050 °C (A and B) and at 1025 °C (C) and then water quenched, producing a uniform austenitic grain size of 30 μm. Tensile tests were run in an Instron testing machine at 63 °C and 23 °C in water, -10 °C and -50 °C in ethyl alcohol, and -196 °C in liquid nitrogen. Two nominal strain rates of \( \varepsilon_1 = 2.2 \times 10^{-4} \text{s}^{-1} \) and \( \varepsilon_2 = 5.6 \times 10^{-5} \text{s}^{-1} \) were employed.

The volume fraction of strain-induced α'-martensite in steel A was monitored by x-ray diffraction using the integrated intensities of the martensite (110), (200), and (211) peaks and the austenite (111), (200), and (220) peaks measured on several prestrained specimens for each test temperature. No evidence of HCP ε'-martensite was found.

**Results and discussion.** True stress-strain curves and corresponding \( f(\varepsilon) \) transformation curves measured at three temperatures and two strain rates are presented in figure 1. The experimental \( \sigma-\varepsilon \) curves of the metastable austenite (steel A) are shown by the solid curves labeled \( \sigma_{\text{exp}} \). The corresponding \( \sigma-\varepsilon \) curves of the stable austenite (steel B) and martensite (steel C) are depicted by the dashed curves labeled \( \sigma_{A} \) and \( \sigma_{A'} \) respectively. The measured \( \sigma_{A} \) curves have been slightly shifted upward to compensate for a small (27 MN/m²) difference in the yield strengths of steels A and B. The \( \sigma_{A'} \) curves of the martensite, which exhibited a uniform elongation of less than 4 pct., were obtained from a power law fit to the homogeneous low-strain measurements and local measurements made during necking.

Over the temperature range covered in figure 1, the metastable austenite exhibited a normal temperature dependence of the yield strength and sigmoidal transformation curves indicative of strain-induced transformation. At the liquid-nitrogen temperature the yield strength was reduced and the transformation curve became linear, indicative of stress-assisted transformation. No transformation was detected at 63 °C out to \( \varepsilon = 0.30 \).

An estimate of the static-hardening contribution to the metastable-austenite flow curve can be made from the \( f(\varepsilon) \), \( \sigma_{A}(\varepsilon) \), and \( \sigma_{A'}(\varepsilon) \) curves using models of two-phase hardening, once assumptions are adopted concerning the distribution of strain between the two phases. The simplest model is the rule of mixtures (RM) based on the assumption that the strain in both phases is equal to the macroscopic plastic strain. The stress-strain curve computed on this basis is shown by the dashed curves labeled RM in figure 1. Ausforming studies indicate that the substructure of deformed austenite is inherited by martensite and that the strengthening contributions of deformation and transformation substructures superimpose. This implies that the flow stress of deformed martensite and that of martensite freshly formed from an equivalently deformed austenite are comparable. Hence the concept of equal plastic strain in both phases of a transforming metastable austenite appears to provide a reasonable approximation, in spite of the changing phase content along the stress-strain curve.

However, the assumption that the effective strain in both phases is also equal to the macroscopic strain is probably not valid, since some of the latter strain arises from a bias of the martensitic transformation shape-change which does not correspond to the working of either phase. The state of plastic strain of the phases would then correspond to the total strain minus a transformation strain, \( \varepsilon_T = \alpha T \), proportional to the amount of transformation, \( \varepsilon_T = \alpha T \). An upper-limit estimate of the coefficient \( \alpha \) can be obtained from the slope of the linear \( f(\varepsilon) \) relation during stress-assisted transformation at -196 °C, giving \( \alpha = 0.12 \). A strain-corrected rule of mixtures (SCRM) can then predict the "static-flow stress", \( \sigma_s \), arising from two-phase hardening according to the relation.

\[
\sigma_s = [1-f] \cdot \sigma_A(\varepsilon = \alpha f) + f \cdot \sigma_{A'}(\varepsilon = \alpha f).
\]
Fig. 1. Experimental flow stress, $\sigma_{\text{exp}}$, and volume fraction martensite, $f$, vs. plastic strain, $\varepsilon$, for metastable austenitic steel A at temperatures indicated. Dashed curves represent the stable austenite flow stress, $\sigma_Y$, the martensite flow stress $\sigma_M$, and the prediction of the rule of mixtures for two-phase hardening, RM. Solid curve, $\sigma_S$, is prediction of strain-corrected rule of mixtures model.

$\varepsilon_1 = 2.2 \times 10^{-4}\text{s}^{-1}$, $\varepsilon_2 = 5.6 \times 10^{-3}\text{s}^{-1}$. 

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The SCRM estimate of the static-hardening behavior from equation 1 is shown as the solid curves labeled $\sigma_5$ in figure 1. The (dashed) uncorrected RM curves can be regarded as an upper-limit estimate of the static-hardening, corresponding to $\alpha=0$.

An attempt was made to determine more directly the static two-phase hardening behavior via a series of prestrain experiments, as represented by the example in figure 2. After deforming the transforming material to a strain $\varepsilon_0$, the static flow stress of the resulting two-phase mixture (in the absence of dynamic transformation softening) was estimated from its flow stress subsequently measured at 63°C (where the austenite is stable) and correcting for its temperature dependence. The latter temperature correction was obtained from the temperature dependence of the flow stress of the stable austenite (B) and martensite (C) at low-temperature prestraining, and included the effect of martensite strain aging on warming to 63°C. The flow curve observed on continued straining at 63°C is shown in figure 2, shifted vertically by a thermal correction increment $\Delta T$ to correspond to the (non-transforming) flow properties at the indicated prestrain temperature of -50°C. (The measured thermal increment for austenite and martensite were slightly different; $\Delta T$ for two phase mixtures was assumed to vary linearly with $\varepsilon$.) Unfortunately, restraining at 63°C was accompanied by a fairly large initial transient which made the flow stress at the prestrain level difficult to assess. To correct for the transient effect, the curve measured at 63°C was fitted to an expression of the form $\sigma = k' (\varepsilon + \varepsilon_0)^n$ as shown by the dotted curve in figure 2, from which the "static" flow stress at $\varepsilon_0$ can be placed at point Y. The uncertainty caused by the transient is worsened by the possibility of some recovery on warming to 63°C which could cause an underestimate of the flow stress of the two-phase mixture. Flow stress points determined in this way are denoted by open circles in figure 1. The points are in reasonable agreement with the $\sigma_5$ curve from the SCRM model, but generally fall somewhat below. In view of the ambiguities in the prestrain experiments, the solid $\sigma_5$ curves are taken as our best estimates of the static-hardening behavior, with the dashed RM curves and prestrain experimental points giving a rough measure of the uncertainty of these estimates.

By any of these measures of $\sigma_5$, comparison with $\sigma_{exp}$ reveals that the transforming material flows at a significantly lower stress, reflecting a substantial dynamic-softening increment associated with operation of the martensitic transformation as a deformation mechanism. This is especially evident at low strains at -50°C where $\sigma_{exp}$ falls below $\sigma_5$. Expressing the flow stress of the transforming material as

$$\sigma = \sigma_5 - \Delta \sigma_d,$$  

(2)

the estimated $\sigma_5$ allows an estimate of the dynamic-softening increment $\Delta \sigma_d$ as designated in figure 1a.

Another series of prestrain experiments, in which continued straining was performed at different temperatures to give various changes of transformation rate, suggested that $\Delta \sigma_d$ (at a fixed prestrain) is proportional to $df/d\varepsilon$. Comparison of $\Delta \sigma_d$ and $df/d\varepsilon$ for the data of figure 1 indicates that the proportionality constant increases with increasing deformation. The latter behavior is analogous to that observed when the plastic flow of metastable austenite is controlled by the stress-assisted mode of transformation (1,2); the transformation-controlled flow stress associated with a fixed transformation rate is then essentially constant and so an increase in $\sigma_5$ should be accompanied by a linearly-related increase in $\Delta \sigma_d$. Accordingly, the ratio $\Delta \sigma_d/df/d\varepsilon$ determined from the data of figure 1 is plotted vs. $\sigma_5$ in figure 3. The points are based on the SCRM $\sigma_5$ curves while the brackets represent the RM and prestrain-experiment estimates. Within the experimental uncertainty, the ratio is found to be proportional to $\sigma_5$ and independent of temperature and strain rate over the range examined. This then defines a relation for $\Delta \sigma_d$ of the form...
Fig. 2 Prestrain experiment for determining static-hardening contribution of two-phase mixture. Transforming material is deformed to point $x$ at $-50^\circ$ C, then tested at $63^\circ$ C without further transformation. Thermally-corrected $63^\circ$ C flow curve indicates static flow stress at point $y$.

$$\sigma = K(e + \epsilon_0)$$

$$\sigma_{50^\circ C, \epsilon_0}$$

$$\sigma_{+50^\circ C}$$

$$\sigma_{63^\circ C + \Delta \sigma}$$

TRUE STRESS, $\sigma$ (MN/m$^2$)

TOTAL PLASTIC STRAIN

Fig. 3. Dependence of dynamic-softening /transformation-rate ratio on static flow stress, $\sigma_5$.

$$E_1 = 2.2 \times 10^{-6}s^{-1}, \quad E_2 = 5.6 \times 10^{-6}s^{-1}$$

Fig. 4. Comparison of $\sigma_{\exp}(c)$ curves of figure 1 with calculated curves from equation 4.
with the solid line in figure 3 giving \( \frac{\Delta a_d}{d} = 5.3 \times 10^{-2} \). Combining equations 1-3 provides a complete constitutive relation for the plastic flow of a metastable austenitic steel:

\[
\sigma = ([1-f] \sigma_y + f \sigma_y'(\varepsilon - \sigma_f) - [1-f] \sigma_s d \varepsilon)
\]

Calculated \( \sigma - \varepsilon \) curves from equation 4 are compared against the experimental curves of figure 1 in figure 4, demonstrating excellent agreement.

Within the regime of strain-induced transformation, equation 4 now allows the prediction of \( \sigma(\varepsilon, \varepsilon_t, T) \) for metastable austenitic steels from knowledge of \( f, \sigma_y, \) and \( \alpha, ' \) as functions of \( \varepsilon, \varepsilon_t, \) and \( T \). It is interesting to note from the data of figure 1 that \( \sigma_y(\varepsilon) \) and \( \sigma_y'(\varepsilon) \) are rather weakly temperature- and rate-dependent so that the large changes in shape of \( \sigma - \varepsilon \) curves shown in figure 4 arise primarily from the behavior of \( f(\varepsilon) \). Thermocouples attached to deforming specimens indicated that the relative reduction of transformation rate with increasing strain rate at \(-50^\circ \text{C}\) is due to a small temperature rise (\(-2^\circ \text{C}\)) occurring in spite of the thin specimen dimensions and presence of the cooling medium.

Conclusions.- Comparison of the flow curves of transforming metastable austenite, stable austenite, and martensite has allowed a separation of the static-hardening and dynamic-softening contributions to the flow behavior of metastable austenite. The flow stress, \( \sigma_s \), associated with the static-hardening behavior of the two-phase mixture is described by a transformation-strain-corrected rule of mixtures. The dynamic-softening effect of the transformation as a deformation mechanism, \( \sigma_d \), is proportional to \( df/d\varepsilon \) and \( \sigma_s \). Combining these effects, a constitutive relation is derived predicting \( \sigma(\varepsilon, \varepsilon_t, T) \) for metastable austenites from the strain-induced transformation kinetics and the flow properties of the two phases.

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