CONSTITUTIVE EQUATIONS FOR STRENGTH AND FAILURE AT ELEVATED TEMPERATURES AND STRAIN RATES IN AUSTENITIC STAINLESS STEELS

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ABSTRACT: Constitutive equations for strength and for ductility of austenitic stainless steels were derived from torsion data between 900 and 1200°C (0.1-5 s⁻¹).

1. INTRODUCTION AND TECHNIQUES: The hot workability of austenitic stainless steels has been reviewed including the effects of alloying and impurity elements (1-4). The present paper will give particular emphasis to the strength and fracture constitutive equations determined for four good quality alloys, 301, 304, 316, and 317, in both the continuous-cast (C) and homogenized worked (W) conditions (Table 1); their behavior in various aspects has been reported earlier (3-21). The torsion testing (5,6,8,11,13,16) was carried out in the range 900-1200°C and 0.1 to 5 s⁻¹ with control and data acquisition by microcomputer; the data was transformed to equivalent stress and strain in the normal manner (3,5,6,11,13,16).

The flow curves exhibited the stress peak, flow softening and steady state regime (5-20) characteristic of dynamic recrystallization (DRX) (1-19,23-25). Optical microscopy revealed that DRX commenced shortly before the peak and occurred repeatedly maintaining almost equiaxed grains to very high strains (8-11,14,16,18,20). Electron microscopy of thin foils showed that the DRX grains contained a dynamically recovered (DRV) substructure similar to that present before the peak (9-11,14,16,26). The sizes of both the DRV subgrains and the DRX grains were inversely related to the peak stress and to the logarithm of Z, a temperature (T) compensated strain rate (9-11,14,16,26). The worked alloys exhibited true fracture strains from 4 to 18, the mechanism being intergranular fissuration impeded by DRX and DRV (1-6,8,11,13,16-18,20,23,25,27). For 301W, 304W, 316W and 317W, the strength and its Z dependence increased, but the grain and subgrain sizes and ductility decreased with rising solute in the order given (6-20). For the cast alloys, the peak stress and strain and the ductility were strongly dependent on the density and distribution of δ-ferrite which induced strain concentrations in the γ-phase leading to enhanced DRX nucleation but also to accelerated interphase cracking (3,5,6,18,19,20).

This paper will examine the constitutive equations relating to
TABLE 1: COMPOSITIONS AND SUMMARY OF CONSTITUTIVE PARAMETERS

<table>
<thead>
<tr>
<th>Alloy</th>
<th>Composition %</th>
<th>Met. Solute %</th>
<th>Q kJ/mol</th>
<th>n</th>
<th>T', K</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>C</td>
<td>Cr</td>
<td>Mo</td>
<td>Ni</td>
<td>exp. mean</td>
</tr>
<tr>
<td>301W</td>
<td>.110</td>
<td>17.12</td>
<td>0.20</td>
<td>7.92</td>
<td>27.24</td>
</tr>
<tr>
<td>304C</td>
<td>.069</td>
<td>18.31</td>
<td>0.08</td>
<td>8.88</td>
<td>29.51</td>
</tr>
<tr>
<td>304W</td>
<td>.062</td>
<td>18.28</td>
<td>0.28</td>
<td>8.27</td>
<td>29.02</td>
</tr>
<tr>
<td>316C</td>
<td>.017</td>
<td>16.92</td>
<td>2.76</td>
<td>12.42</td>
<td>34.60</td>
</tr>
<tr>
<td>316W</td>
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<td>16.40</td>
<td>2.73</td>
<td>12.05</td>
<td>33.67</td>
</tr>
<tr>
<td>317C</td>
<td>.035</td>
<td>18.60</td>
<td>3.22</td>
<td>13.88</td>
<td>37.87</td>
</tr>
<tr>
<td>317W</td>
<td>.035</td>
<td>18.60</td>
<td>3.23</td>
<td>13.68</td>
<td>37.87</td>
</tr>
</tbody>
</table>

* Number of reports referenced.

the peak stress, to dynamic recrystallization, to the saturation stress arising from DRV and to failure. The peak strength will be a brief summary but will also include mean parameter values derived from 70 reports in the literature. The failure discussion will include the analyses proposed by Gittins and Sellars (27,28) and by Elfmark (29).

2. PEAK STRESS: SINH AND ARRHENIUS RELATIONS: The peak stress $\sigma_p$ and $\epsilon_p$ decline as $T$ rises, $\epsilon$ decreases and solute increases but the former is raised and the latter reduced by $\delta$-ferrite segregated in solidification (5,6,8,20). The following relationships similar to these in creep have been examined:

\[
A' \sigma_p^n = \epsilon \exp \left( \frac{Q'_H}{RT} \right) = Z' \\
A'' \exp \beta \sigma_p^n = \epsilon \exp \left( \frac{Q''_H}{RT} \right) = Z'' \\
A (\sinh \alpha \sigma_p^n) = \epsilon \exp \left( \frac{Q_H}{RT} \right) = Z
\]

where $A'$, $A''$, $A$, $n$, $\alpha$, $\beta \approx \alpha n$, $R = (8.31 \text{ kJ/mol} \cdot \text{K})$, $Q'_H$, $Q''_H$, and $Q_H$ are constants. The power law (Eqn 1) was found suitable at high $T$, low $\epsilon$ but broke down for $\sigma > 100$ MPa (12,13,16). The exponential law, Eqn 2, was found satisfactory for the stronger as-cast material (5,6,19) but for the worked material broke down for $\sigma < 100$ MPa (6,9,12,13,17). The sinh law (Eqn 3 with $\alpha = 0.012 \text{ MPa}^{-1}$) was found to fit the data for as-cast and worked alloys (6-13,15-17,20-22). The constants in Eqn 3 for all materials and in Eqn 2 for as-cast metal are listed in Table 1. These relationships are shown in a plot of $\sigma_p$ vs $Z$ (Fig. 1); the reorganization of the data into a single line facilitates interpolation and extrapolation (12,13,17,20).

A search of the literature uncovered data for 70 alloys which permitted the determination of mean values of the constants for average compositions of each alloy (Table 1) (12,13,16,20). In addition, the activation energy was found to depend linearly on the total metallic solute (12):

\[
Q_H = 25 \pm 13.5 \text{ (wt% solute)}
\]

An inverted form of Eqn 3 has been proposed by Tanaka (30).

\[
\sigma = \frac{1}{\alpha} \sinh^{-1} \left( \epsilon \exp \left( \frac{Q}{RT} \left[ (1/T) - (1/T') \right) \right) \right)
\]

where the constant $T' = (Q_H / R \ln A)$ is a constant for the material being about $0.8T$ (Table 1) (12,13,16). Finally the data was corrected for deformational heating which results in greater $T$ rise at higher $\epsilon$. 