Elevated Temperature Ductility of Types 304 and 316 Stainless Steel

V. K. Sikka
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Date Published: December 1978

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OAK RIDGE NATIONAL LABORATORY
Oak Ridge, Tennessee 37830
operated by
UNION CARBIDE CORPORATION
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DEPARTMENT OF ENERGY
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ELEVATED TEMPERATURE DUCTILITY OF TYPES 304 AND 316 STAINLESS STEEL

V. K. Sikka

ABSTRACT

Austenitic stainless steel types 304 and 316 are known for their high ductility and toughness. However, the present study has shown that certain combinations of strain rate and test temperature can result in a significant loss in elevated-temperature ductility of these materials. Such a phenomenon is referred to as ductility minimum. The strain rate, below which ductility loss is initiated, decreases with decrease in test temperature. For example, the strain rate at the ductility minimum point decreased for unaged type 316 stainless steel from about $5 \times 10^{-5}$ to $3 \times 10^{-9}$/s for a decrease in test temperature from 760 to 538°C. The corresponding ductility values (reduction of area) decreased from 65 to 10%. Besides strain rate and temperature, the ductility minimum was also affected by nitrogen content and thermal aging conditions. For example, the minimum values of total elongation and reduction of area decreased at 649°C from 41 to 14% and 39 to 14%, respectively, for an increase in nitrogen content from 0.039 to 0.15%.

Thermal aging at 649°C was observed to eliminate the ductility minimum at 649°C in both types 304 and 316 stainless steel. In fact, such an aging treatment resulted in a higher ductility than the unaged value. Aging at 593°C still resulted in some loss in ductility.

The current results suggest that ductility-minimum conditions for stainless steel should be considered in design, thermal aging data analysis, and while studying the effects of chemical composition.

Current results have been discussed in terms of a proposed dynamic dislocation recovery mechanism.

INTRODUCTION

Types 304 and 316 austenitic stainless steel are known for their high ductility and toughness. However, the present study has shown that certain combinations of strain rate and temperature can result in significant loss in elevated-temperature ductility of these materials. Such a phenomenon is observed in several pure metals and alloys\(^1\) and is often referred

\(^1\)Work performed under U.S. DOE/RRT 189a OH050, Mechanical Properties for Structural Materials.
to as a ductility minimum. A typical characteristic of this minimum is a rapid drop in total elongation and reduction of area at a test temperature in the neighborhood of 0.5–0.6 $T_m$ ($T_m$ is the melting point in K). Values of these ductility minima frequently fall below 10%, as measured by elongation.

The first report on the ductility minimum in 18-8 stainless steel was by Newell\(^2\) in 1933. Newell investigated the elevated-temperature tensile reduction of area for stainless steels after four different heat treatments to produce different grain sizes. He found that, although the ductility minimum in 18-8 stainless steel occurs over essentially the same temperature range (850–900°C) for all treatments, the initiation temperature for a rapid drop in ductility decreases with increasing grain size. Furthermore, coarse grain material showed a significantly lower ductility than hot-rolled fine-grain material. For example, ductilities at 600°C for fine and coarse grain material were 60 and 38%, whereas at 700°C they were 62 and 20%, respectively.

Austenitic stainless steels are frequently used in the construction of both nuclear and non-nuclear energy systems and will be subjected to elevated temperatures for long periods. Therefore, it is important to determine the factors and interrelationships concerning the occurrence of this minimum, including the effects of long-term thermal exposure. The purpose of this paper is to:

1. illustrate conditions under which a ductility minimum can occur;
2. illustrate effect of nitrogen on ductility-minimum conditions;
3. illustrate effects of long-term thermal aging on ductility; and
4. explain results in terms of microstructure and dislocation substructure data.

**EXPERIMENTAL DATA**

Experimental data presented in this paper are primarily from 25- and 51-mm-thick plates from a single heat of type 304\(^3,4\) and a 16-mm-thick plate of type 316.\(^5\) Chemical analysis and grain sizes of these heats are listed in Table 1. The test specimens were threaded-end bars having
Table 1. Chemical Composition and Grain Size of Types 304 and 316 Stainless Steel Used in the Present Investigation

<table>
<thead>
<tr>
<th>Type</th>
<th>C</th>
<th>N</th>
<th>P</th>
<th>Ni</th>
<th>Mn</th>
<th>Cr</th>
<th>Si</th>
<th>Mo</th>
<th>S</th>
<th>Al</th>
</tr>
</thead>
<tbody>
<tr>
<td>304a</td>
<td>0.047</td>
<td>0.031</td>
<td>0.029</td>
<td>9.58</td>
<td>1.22</td>
<td>18.50</td>
<td>0.47</td>
<td>0.10</td>
<td>0.012</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>316b</td>
<td>0.065</td>
<td>0.031</td>
<td>0.022</td>
<td>13.86</td>
<td>1.88</td>
<td>16.46</td>
<td>0.51</td>
<td>2.44</td>
<td>0.018</td>
<td>&lt;0.02</td>
</tr>
</tbody>
</table>

*Laboratory annealed for 0.5 h at 1093°C. Grain sizes for 25- and 51-mm plate were 230 and 280 μm, respectively.

*Laboratory annealed for 0.5 h at 1065°C. Grain sizes for 16-mm plate for the as-received and reannealed conditions were 50 and 90 μm, respectively.

A gage diameter of 6.35 mm and reduced section of 57.2 mm. Specimens were lathe machined, cleaned, and subjected to the following heat-treating conditions:

1. as-received or mill-annealed — contains residual cold work due to thermomechanical processing;
2. reannealed or laboratory annealed — consists of holding at 1093°C for type 304 and 1065°C for type 316 for 0.5 h followed by fast cooling.
3. thermally aged — consists of thermal exposure of specimens at the test temperature for varying times (7 to 10,000 h).

Tensile tests were performed in air at temperatures in the range from room temperature to 760°C and strain rates from $1 \times 10^{-4}$ to 5/min. One test at 482°C was performed at $2.6 \times 10^{-6}$/min. The strain rate was controlled by crosshead speed. Additional details of tensile testing can be found elsewhere.

Creep data on these heats are also used in this paper to show the strain rate effects. Experimental results presented in this paper also include data by Cullen and Davis.
RESULTS

Unaged Material

Mill-annealed (as received) and reannealed (laboratory annealed).

Temperature and Strain Rate Dependence

Total elongation and reduction of area data for type 304 stainless steel are plotted as a function of temperature in Figs. 1 and 2. Data in Fig. 1 are on 25-mm-thick plate and those in Fig. 2 are on 51-mm-thick plate. These data were generated at strain rates in the range of 0.0001 to 5/min. One data point was also obtained at a strain rate of 0.0000026/min. These figures illustrate that both total elongation (TE) and reduction of area (RA) show drops in their values in the temperature range of 450 to 750°C (0.43 to 0.61 $T_m$, $T_m$ = melting point, 1673 K). The temperature at which the drop in TE and RA initiated decreased with decreasing strain rate. For example, it occurred at 593°C for a strain rate of 0.05/min (Fig. 1) and at about 450°C for a strain rate of 0.0001/min. The drop in

![Fig. 1. Ductility Versus Test Temperature for 25-mm Plate of Reference Heat (9T2796) of Type 304 Stainless Steel. (a) Tensile total elongation. (b) Reduction of area.](image)
ductility, once initiated, continues to decrease until it goes through a minimum value (often called the ductility-minimum point) and then the ductility increases again at some higher test temperature. The ductility at the minimum point was also found to decrease with the decreasing strain rate. For example, a value of RA was about 42% for a strain rate of 0.05/min (Fig. 1) and about 19% for a strain rate of 0.0001/min. Figure 3 shows the similar ductility minima results for type 316 stainless steel.

Reduction of area isotherms as a function of minimum creep rate (during a creep test) or tensile test strain rate are shown in Fig. 4 for 51-mm plate of type 304 stainless steel. Data were generated on material in the reannealed condition and include results on creep rupture times of 30,000-h duration. Similar data on type 316 stainless steel are shown in Fig. 5. The creep-rupture times for type 316 stainless steel were only 15,000-h duration. For type 316 stainless steel (Fig. 5) the following observations can be made:
Fig. 3. Ductility Versus Test Temperature for 16-mm Plate of Reference (8092297) of Type 316 Stainless Steel. (a) Tensile total elongation. (b) Reduction of area.

Fig. 4. Reduction of Area as a Function of Minimum Creep Rate and Tensile Test Strain Rate for Reannealed Reference Heat of Type 304 Stainless Steel.
1. The strain rate below which ductility loss is initiated decreases with decreasing test temperature. This is indicated by the arrows.

2. The strain rate at which the minimum occurs decreases with decreasing test temperature. For example, it decreased from about $5 \times 10^{-5}$ to about $3 \times 10^{-9}/s$ for a decrease in test temperature from 760 to 538°C.

3. The ductility value at the minimum point also decreased with decreasing test temperature. For example, the RA values decreased from 65 to 10% for a decrease in test temperature from 760 to 538°C.

4. At strain rates below the ductility-minimum strain rate, the ductility values appear to increase at all test temperatures. However, for test temperatures of 649 to 704°C, the ductility values are starting to show a second drop following the increase. Similar decreases might also occur at the other temperatures, 538, 593, and 760°C at further lowering in strain rate or during the longer creep-rupture times.

For type 304 stainless steel (Fig. 4) the following observations can be made and compared with the results on type 316 stainless steel:

1. The strain rate below which ductility loss is initiated shows a decrease with decrease in test temperature. This is indicated by arrows in Fig. 4.
2. The ductility-minimum point itself is not as well-defined as in type 316 stainless steel. However, it still occurs at decreasing strain rates with decreasing test temperatures as shown by points A, B, C, and D.

3. The ductility values at the minimum point also decrease with decreasing test temperature.

4. There are some indications of increase in ductility at strain rates lower than the ductility-minimum strain rate. It should, however, be noted that the RA values approach the 5–10 range for creep-rupture times of 30,000 h. This appears to happen independent of the test temperature.

Effect of Nitrogen Content on Ductility Minimum Characteristics of Type 316 Stainless Steel

The creep and tensile reduction of area and total elongation data are plotted (Fig. 6) as a function of minimum creep rate or tensile test strain rate for five heats of type 316 stainless steel. One additional heat investigated contained 0.11% N and 16% ferrite by volume. The current analysis is limited to Cullen and Davis\(^8\) data at a single test temperature of 649°C.

Reduction of area and total elongation values decreased with decreasing strain rate to a minimum value and then increased. The strain rate at the minimum ductility, the total elongation and reduction of area at the minimum, and their values at a strain rate of \(1 \times 10^{-8}/s\) are summarized in Table 2.

The strain rate causing minimum in ductility decreased from \(2 \times 10^{-6}\) to \(5 \times 10^{-8}/s\) as the nitrogen content increased from 0.03 to 0.15% (Fig. 7). The total elongation and reduction of area values decreased from 41 to 14% and 39 to 14%, respectively, for an increase in nitrogen content from 0.039 to 0.15% (Fig. 8). A heat containing 0.11% N plus 16 vol % ferrite showed only a slight minimum at a strain rate of \(4.5 \times 10^{-8}/s\). The reduction of area of this heat at the ductility minimum point was 54%, as opposed to 14% observed for a heat of similar nitrogen content but without any ferrite. Generally, sigma phase is known to decrease ductility and toughness. However, in the heat with 16% ferrite, almost all of it transformed to sigma plus austenite, ductility values were still very high.
Fig. 6. (a) Total Elongation and (b) Reduction of Area as Functions of Minimum Creep Rate or Tensile Test Strain Rate. Tests were conducted at 649°C on type 316 stainless steel containing nitrogen in the range 0.039 to 0.15%. Source: T. M. Cullen and M. W. Davis, "Influence of Nitrogen and the Creep-Rupture Properties of Type 316 Steel," Elevated Temperature Properties as Influenced by Nitrogen Additions to Types 304 and 316 Austenitic Stainless Steels, Spec. Tech. Publ. 522, American Society for Testing and Materials, Philadelphia, 1973, pp. 60-78.
Table 2. Ductility Characteristics at 649°C for Several Heats of Type 316 Stainless Steel Containing 0.039 to 0.15% Nitrogen\(^a\)

<table>
<thead>
<tr>
<th>Nitrogen (%)</th>
<th>Ferrite (Vol %)</th>
<th>Strain Rate for Minimum Ductility ( (s^{-1}) )</th>
<th>Ductility Values, %, at Minimum Ductility Point</th>
<th>Ductility Values, %, at ( 1 \times 10^{-8}/s )</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Reduction of Area</td>
<td>Total Elongation</td>
</tr>
<tr>
<td>0.039</td>
<td></td>
<td>( 2 \times 10^{-6} )</td>
<td>39</td>
<td>41</td>
</tr>
<tr>
<td>0.044</td>
<td></td>
<td>( 2.5 \times 10^{-6} )</td>
<td>36</td>
<td>32</td>
</tr>
<tr>
<td>0.070</td>
<td></td>
<td>( 1.6 \times 10^{-7} )</td>
<td>28</td>
<td>24</td>
</tr>
<tr>
<td>0.099</td>
<td></td>
<td>( 1.5 \times 10^{-7} )</td>
<td>14</td>
<td>14</td>
</tr>
<tr>
<td>0.15</td>
<td></td>
<td>( 5.0 \times 10^{-8} )</td>
<td>17</td>
<td>15</td>
</tr>
<tr>
<td>0.11</td>
<td>16</td>
<td>( 4.5 \times 10^{-6} )</td>
<td>54</td>
<td>65</td>
</tr>
</tbody>
</table>


\(^b\)Based on minimum in reduction of area.

\(^c\)Extrapolated to estimate values at \( 1 \times 10^{-8}/s \).

\(^d\)Curves show downward trend and are thus not easy to extrapolate to \( 1 \times 10^{-8}/s \).

---

Fig. 7. Strain Rate at Ductility Minimum as a Function of Nitrogen Content for Type 316 Stainless Steel Tested at 649°C. Ductility minimum strain rate data were taken from Fig. 6.
Fig. 8. (a) Total Elongation and (b) Reduction of Area at Minimum Ductility Point as Functions of Nitrogen Content for Type 316 Stainless Steel Tested at 649°C. Ductility data were taken from Fig. 6.
AGED MATERIAL

Laboratory Aged Material

The tensile properties of thermally aged type 316 stainless steel are summarized in Tables 3 and 4. The data represent aging times of 10,000 h and aging temperatures in the range 427 to 704°C. Tensile tests were performed at both room temperature and the aging temperature. All tests were performed at a strain rate of 0.004/min.

Table 3. Room-Temperature Tensile Properties of 16-mm Plate of Reference Heat 8092297 of Type 316 Stainless Steel

<table>
<thead>
<tr>
<th>Material Condition</th>
<th>Aging Temperature (°C)</th>
<th>Strength, MPa</th>
<th>Elongation, %</th>
<th>Reduction of Area (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>0.2% Yield</td>
<td>Ultimate Tensile Uniform</td>
<td>Total</td>
</tr>
<tr>
<td>A 240 Unaged</td>
<td></td>
<td>228</td>
<td>583</td>
<td>60.5</td>
</tr>
<tr>
<td>A 240 482</td>
<td></td>
<td>235</td>
<td>583</td>
<td>53.1</td>
</tr>
<tr>
<td>A 240 593</td>
<td></td>
<td>223</td>
<td>589</td>
<td>47.3</td>
</tr>
<tr>
<td>A 240 649</td>
<td></td>
<td>216</td>
<td>596</td>
<td>42.8</td>
</tr>
<tr>
<td>Reannealed Unaged</td>
<td></td>
<td>211</td>
<td>571</td>
<td>62.0</td>
</tr>
<tr>
<td>Reannealed 482</td>
<td></td>
<td>222</td>
<td>570</td>
<td>53.7</td>
</tr>
<tr>
<td>Reannealed 593</td>
<td></td>
<td>219</td>
<td>586</td>
<td>47.7</td>
</tr>
<tr>
<td>Reannealed 649</td>
<td></td>
<td>211</td>
<td>593</td>
<td>43.2</td>
</tr>
</tbody>
</table>

*Tested as mill-annealed (A 240), reannealed (0.5 h at 1065°C), and aged 10,000 h. Test strain rate was 0.004/min.

The room-temperature yield strength was only slightly affected by thermal aging at 482, 593, or 649°C. The ultimate tensile strength showed an increase by thermally aging at 593 and 649°C. Thermal aging at 482°C did not affect any of the room-temperature properties. All ductility quantities, uniform elongation (UE), total elongation, and reduction area were decreased by thermal aging for 10,000 h at 593 and 546°C. This will be discussed again in the next few paragraphs.
The 0.2% yield strength at the aging temperature also changed only slightly. The ultimate tensile strength showed a decrease by thermal aging at all temperatures; the decrease was greatest for 593°C. The various ductility quantities showed different behavior.

The reduction of area data are plotted as a function of aging time for three different aging temperatures in Fig. 9. The RA values remain unaffected by thermal aging at 482°C. Thermal aging at 593°C decreases RA: the values drop from 66 to 57% after 10,000 h. At 649°C RA drops initially but shows a substantial increase at longer aging time. Values increase from 49% to approximately 70% after 10,000 h.
Fig. 9. Reduction of Area as a Function of Aging Time for the Reference Heat (8092297) of Type 316 Stainless Steel. Specimens were aged and tested at (a) 482, (b) 593, and (c) 649°C.

The UE, TE, and RA of specimens aged for 10,000 h and tested at both room temperature and aging temperature are compared with similar data on mill-annealed and reannealed specimens in Figs. 10 and 11. At room temperature all ductility quantities decreased to an extent that increased with increasing aging temperature. For the mill-annealed material, aging for 10,000 h at 649°C decreased UE from 60 to 43%, TE from 74 to 52%, and RA from 80 to 55%. The UE, TE, and RA values changed very little from thermal aging and testing at 482°C. Thermal aging at 593°C decreases all three ductility quantities. Thermal aging at 649°C decreases UE but increases both the TE and RA. This is observed for material aged in both the mill- and laboratory-annealed conditions.
The increase in RA at 649°C due to aging at 649°C without stress was observed for aging under stress. For example, a specimen of type 316 stainless steel creep tested at 649°C and 124 MPa for 1983 h produced a plasticity and creep strain of 17.32%. When tensile tested, this specimen showed an RA value of 55.9%, as compared with 48.7% observed for the unaged material.
Material Removed from Service

Early in 1968 the junction header (Fig. 12) in Philadelphia Electric's Eddystone No. 1 Station was removed from service because of severe cracking on its inner surface. This header had accumulated over 51,000 h of service at around 621°C since the unit was commissioned late in 1959. A part of this header was made available to ORNL by Cullen of Combustion Engineering, Chattanooga, Tenn., in 1975. We made tensile specimens from this header and put them in the aging furnace at 621°C for additional exposure. A few of these specimens were removed from the aging furnace after an additional 21,000 h. Therefore, these specimens represent a total
exposure period of 72,000 h. Three of the as-removed specimens were reheat-treated to obtain the unaged properties. Tensile tests were performed at room temperature, 593, and 649°C on both the reheat-treated and aged specimens. Results from these tests along with previous data are summarized in Table 5. Previous results were obtained from tests performed at a strain rate of 0.05/min, whereas the current tests were performed at a strain rate of 0.005/min.

Thermal exposure for 72,000 h at 621°C appears to increase yield and ultimate tensile strengths over those of the as-reheat-treated material. The changes in ultimate tensile strength at elevated temperatures were smaller than those observed for tests at room temperature. The changes in ductility depended on the quantity selected. For example, uniform elongation decreased at all test temperatures [Fig. 13(a)]. Total elongation decreased only at room temperature and 593°C and increased slightly at
Table 5. Summary of Tensile Data on Reheat-Treated and Aged Type 316 Forged Header Removed from Philadelphia Electric's Eddystone No. 1 Station

<table>
<thead>
<tr>
<th>Test Temperature (°C)</th>
<th>Strength MPa (ksi)</th>
<th>Elongation, %</th>
<th>Reduction of Area (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Yield</td>
<td>Ultimate</td>
<td>Uniform</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Reheat-Treated for 0.5 h at 1065°C</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>25</td>
<td>222 (32.2)</td>
<td>534 (77.5)</td>
<td>46.9</td>
</tr>
<tr>
<td>593</td>
<td>99 (14.4)</td>
<td>374 (54.2)</td>
<td>38.2</td>
</tr>
<tr>
<td>593</td>
<td>98 (14.2)</td>
<td>352 (51.1)</td>
<td>32.6</td>
</tr>
<tr>
<td>649</td>
<td>97 (14.1)</td>
<td>287 (41.6)</td>
<td>26.1</td>
</tr>
<tr>
<td>As-Removed From Service (51,000 h at 621°C)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>25</td>
<td>308 (44.6)</td>
<td>712 (103.2)</td>
<td>26.8</td>
</tr>
<tr>
<td>482</td>
<td>215 (31.2)</td>
<td>488 (70.8)</td>
<td>15.7</td>
</tr>
<tr>
<td>538</td>
<td>183 (26.6)</td>
<td>445 (64.6)</td>
<td>16.9</td>
</tr>
<tr>
<td>593</td>
<td>190 (27.6)</td>
<td>428 (62.1)</td>
<td>13.9</td>
</tr>
<tr>
<td>593</td>
<td>181 (26.3)</td>
<td>435 (63.1)</td>
<td>14.9</td>
</tr>
<tr>
<td>649</td>
<td>173 (25.1)</td>
<td>366 (53.1)</td>
<td>16.5</td>
</tr>
<tr>
<td>As Removed From Service Plus Aged (Total Time 72,000 h at 621°C)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>25</td>
<td>278 (40.3)</td>
<td>676 (98.1)</td>
<td>22.5</td>
</tr>
<tr>
<td>593</td>
<td>177 (25.7)</td>
<td>399 (57.9)</td>
<td>18.3</td>
</tr>
<tr>
<td>649</td>
<td>169 (24.5)</td>
<td>312 (45.2)</td>
<td>14.2</td>
</tr>
</tbody>
</table>

Tests performed at 0.05/min – all other tests at 0.005/min.

b As removed from service plus aged for 21,000 h at 621°C at
ORNL – total aging time 72,000 h.

649°C [Fig. 13(b)]. Reduction of area also decreased at room temperature and 593°C and approached the value for unaged specimens at 649°C [Fig. 13(c)]. The changes in ductility were affected by the tensile test strain rate.

The following observations can be made from these data:

1. Type 316 stainless steel retains about 15% uniform elongation at both room and high temperature even after a thermal exposure of 72,000 h at 621°C.

2. The general concept that aging always decreases tensile ductility is not true. The results presented in Table 5 and Fig. 13 show that while uniform elongation always decreases, total elongation and reduction of area may increase under certain test conditions.

3. The forged header showed extensive surface cracking in spite of its high ductility after long-term thermal exposure at 621°C. The surface cracking was attributed by Cullen9 to thermal fatigue and not to reduced ductility due to thermal aging.
Fig. 13. Ductility as a Function of Test Temperature for Type 316 Stainless Steel Specimens Taken from the Header. (a) Uniform elongation. (b) Total elongation. (c) Reduction of area. Reheat-treated (0.5 hr at 1065°C), as-removed from service (51,000 hr exposure), and additionally aged (total aging time 72,000 hr).
The very fact that the ductility minimum occurs both in pure metals and in complex alloys suggests that the ductility-minimum mechanism is not precipitation related. However, a proposed mechanism should be able to explain the observed effects of long-term thermal aging, strain rate, composition variation, and prior creep. To postulate a suitable mechanism, we have chosen to examine the dislocation substructure characteristics of a pure metal and those of stainless steels (Fig. 14). This figure shows that the ductility minimum in both copper and stainless steel occurs at a temperature beyond which dislocation cells or subgrains increase sharply in size and the free dislocation density drops rapidly. Previous workers have shown that dislocation cells (characterized by dislocation tangle boundaries) form during the tensile deformation mode, and the subgrains (characterized by dislocation network boundaries) form in the creep range.

Fig. 14. Dislocation Cell or Subgrain Size and Mobile Dislocation Density as Functions of Homologous Temperature for Copper and Types 304 and 316 Stainless Steel.
The exact dislocation configuration depends on the stacking fault energy, test temperature, tensile test strain rate, and creep stress. The dislocation cells form as a result of dislocation glide, whereas subgrains form as a result of dislocation climb. The dislocation climb occurs by the diffusion of vacancies or interstitials to or from the site of the dislocation. Thus, dislocation climb will depend on the flux and diffusion rate of vacancies. At temperatures where subgrains form, the diffusion rate is high enough for the vacancies to travel across the grain.

Close to the transition temperature (temperature beyond which dislocation substructure changes) diffusion rates will be slow, and therefore only dislocations near the grain boundary area will be able to climb. Such a process will introduce a dynamic dislocation recovery near the grain boundary area. If such a process occurs, deformation will concentrate primarily in these narrow zones next to the grain boundaries. The concentrated deformation in these zones will most likely nucleate grain boundary cracks. Once again, because of slow diffusion rates, the stress concentration at the tip of cracks will not relax as quickly as possible at higher temperature and therefore, several of these cracks can interlink to give failure with low ductility.

At the higher temperatures deformation can take place across the entire grain, and the grain boundary cracks formed by sliding process can be blunted by dislocation recovery. Thus, the higher ductility at higher temperature is a result of possible deformation across the entire grain and the delayed crack-linking process.

At temperatures below the minimum, there is essentially no diffusion, and the deformation is primarily concentrated inside the grains. The grain boundary sliding is also negligible at these lower test temperatures. Thus, deformation continues until fracture occurs by a transgranular process. Such a process results in high ductility. In summary, it is suggested that the ductility minimum occurs under temperature and strain-rate conditions where only limited dynamic dislocation recovery is possible near the grain boundaries. Microstructures (Fig. 15) of type 316 stainless steel specimens tested below, at, and above the minimum-ductility temperature illustrate the general observation of the overall mechanism.
The proposed mechanism can explain the observation on types 304 and 316 stainless steel as follows:

1. Decreasing the tensile test strain rate decreases the temperature at which minimum occurs (Figs. 1-3). This observation is easily explained by the fact that lowering the strain will provide sufficient time for vacancy diffusion to introduce dynamic dislocation recovery near the grain boundaries, even at lower temperatures.

2. Lower ductility values are observed for the ductility minimum at the lower temperatures (Figs. 1-7). Such an observation is expected because at lower temperatures the dynamic dislocation recovery zone will be narrowed, so the intergranular cracks will nucleate and interlink without significant deformation of matrix.
3. For a given temperature (649°C), the strain rate at which the ductility is a minimum decreases with increasing nitrogen content (Figs. 6 and 7). This observation is explained by the fact that the dislocation climb process is retarded by the interstitial nitrogen atoms moving faster than the vacancies to the dislocations. Thus, for a given test temperature, long test durations, lower creep rates, or tensile strain rate will be required to achieve a ductility minimum in high-nitrogen heats than in low-nitrogen heats.

4. Lower values of ductility are observed at the minimum for the higher nitrogen-containing type 316 stainless steel (Figs. 6 and 8). This observation is probably a consequence of narrower dynamic dislocation recovery zones for higher nitrogen-containing type 316 stainless steel.

5. The ductility is greater at strain rates lower than that at the minimum (Figs. 1–6). This most likely is a consequence of grain boundary precipitates, which modify the grain boundary sliding process. Our previous work\textsuperscript{12} showed that long-term thermal aging at 649°C can retard grain boundary cavitation in types 304 and 316 stainless steel.

6. Thermal aging at 649°C decreases uniform elongation but increases total elongation and reduction of area (Figs. 10, 11, and 13). The uniform elongation decreases as a consequence of intragranular precipitation. The total elongation and reduction of area are expected to increase as a consequence of increased dynamic dislocation recovery zone (due to increased dislocation climb rate because carbon is tied up as carbides), and from grain boundary sliding being retarded by the precipitates.

Micrographs in Fig. 16 show a reheated specimen to have grain boundary cracks even in the region away from the fracture, but the aged specimen to have none. The lowering of ductility by thermal aging at 593°C is probably a result of formation of dynamic dislocation recovery regions due to an increased vacancy diffusion rate. This can happen because of the depletion of carbon from the system. The dynamic dislocation recovery zone apparently was not present in the unaged specimen at the same strain rate.

7. Total elongation and reduction of area are increased by previous creep deformation at 649°C. This is possible because previous creep deformation removes carbon from the system as carbides on dislocations and grain boundaries. The carbon-depleted matrix has a higher vacancy
Fig. 16. Optical Microstructure of Type 316 Stainless Steel Specimens Taken from the Header. (a) Reheat-treated (0.5 h at 1065°C). (b) Thermally aged (72,000 h at 621°C). The specimens were tensile tested at 649°C. The microstructures are from the uniform section away from the fracture. Note the presence of intergranular cavities in the reheat-treated specimen and their absence in the aged specimen.

diffusion rate (because the probability of forming a vacancy-carbon complex is less likely), and thus a large dynamic recovery zone is formed. Also, the precipitates at the grain boundaries will retard the grain boundary sliding process.

5. Ductility is high at the minimum for ferrite-containing type 316 stainless steel (Figs. 6 and 8). This represents a two-phase system in which ferrite transforms to sigma phase during testing. It is not clear at present how the sigma phase, commonly known to reduce ductility, increases the ductility of type 316 stainless steel.

SUMMARY AND CONCLUSION

Effects of several variables on the tensile and creep ductility of types 304 and 316 stainless steel are presented. The variables presented
include effects of test temperature, strain rate, nitrogen content, thermal aging (laboratory aged and material removed from service), and prior creep deformation. A mechanism based on dynamic dislocation recovery is presented to explain the observed results. The following are some important conclusions:

1. A ductility minimum with ductility values of about 10% was shown for unaged types 304 and 316 stainless steel in the temperature range of 450 to 750°C (0.43 to 0.61 Tm).

2. The strain rate and the ductility at the ductility minimum point decreased with decreasing test temperature. For example, the strain rate at the ductility minimum point decreased for type 316 stainless steel from about $5 \times 10^{-5}$ to about $3 \times 10^{-9}$/s for a decrease in test temperature from 760 to 538°C. The corresponding ductility values (reduction of area) decreased from 65 to 10%.

3. Minima in total elongation and reduction of area were observed for the tensile and creep data at 649°C on type 316 stainless steel containing nitrogen in the range of 0.039 to 0.15%. The strain rate giving the minimum ductility decreased from $2 \times 10^{-6}$ to $5 \times 10^{-8}$/s for an increase in nitrogen content from 0.039 to 0.15%. The total elongation and reduction of area values decreased from 41 to 14% and 39 to 14%, respectively, for an increase in nitrogen content from 0.039 to 0.15%.

4. Thermal aging at 649°C eliminated the ductility minimum at test temperature of 649°C and, in fact, resulted in much higher ductility values than the unaged material. Aging at 593°C still resulted in some loss in total elongation (TE) and reduction of area (RA) at 593°C. Thermal aging at 482°C produced essentially no change in TE and TA at 482°C. However, room-temperature ductility showed a drop in the aged condition as compared to unaged properties. The extent of drop increased with increase in aging temperature from 482 to 649°C.

5. Tensile tests on a type 316 stainless steel header removed from Philadelphia Electric's Eddystone No. 1 Station showed the following: (a) about 15% uniform elongation is retained at both room and high temperature, even after thermal exposure of 72,000 h at 621°C; (b) while uniform elongation decreased at all test temperatures, total elongation and reduction of area showed values equal to or even slightly higher than the reheat-treated values at 649°C; and (c) thermal aging of pieces from the header is continuing toward 100,000 h.
6. Results presented in this paper yield several important observations and suggestions for analysis of ductility data on stainless steel.

a. Ductility can show a large drop in the unaged condition under proper conditions of temperature and strain rate and therefore, should be considered when designing under those conditions.

b. Thermal aging at 649°C can eliminate, but it can also produce higher ductility values at 649°C than alternative treatments of material (unaged). This aspect should be considered while analyzing the effects of thermal aging because these effects contradict the general expectation of loss in ductility due to thermal aging.

c. Effects of nitrogen content on ductility-minimum conditions suggest that care should be taken while studying the effects of nitrogen or other elements on mechanical properties. For example, the higher nitrogen level would be considered detrimental for short-term ductility and useful for the long-term ductility. Thus, the final results may require a qualification based on whether the short- or long-term properties are of interest and on the associated temperature, strain rate, and material condition.

ACKNOWLEDGMENTS

The author gratefully acknowledges L. T. Ratcliff for performing tensile tests, R. H. Baldwin for analyzing tensile data, and C. W. Houck for metallography. We also wish to thank Nan Richards for editing and Denise Jackson for preparing the manuscript for reproduction.

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