INFLUENCE OF LABORATORY ANNEALING ON TENSILE PROPERTIES
AND DESIGN STRESS INTENSITY LIMITS FOR
TYPE 304 STAINLESS STEEL*

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ABSTRACT

The influence of reannealing (laboratory annealing) on yield and ultimate tensile strength values of 19 heats of type 304 stainless steel was determined. Most heats were reannealed at 1065°C for 0.5 hr. The reannealed properties were used to determine the influence of reannealing on time-independent design stress intensity limits ($S_m$). The major findings are as follows:

1. Reannealing lowered the 0.2% yield strength versus temperature curve by approximately 42 MPa over the range from room temperature to 649°C.

2. The estimated $S_m$ values for reannealed material were 24 to 28 MPa lower than the current code values.

3. Reannealing appears to influence the $S_m$ value sufficiently to warrant the consideration of separate values of $S_m$ in Sect. III of the Boiler and Pressure Vessel Code and Code Case 1592 for "as-received" and reannealed material.

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1. INTRODUCTION

Mechanical properties are commonly tested on structural materials in the mill-annealed (as-received) condition. However, the size, shape, and tolerance requirements of various products (e.g., tube, pipe, plate, and bar) frequently require final finishing operations, which may consist of straightening, rolling, or drawing passes. These processes introduce varying amounts of cold work or residual stresses in the mill-annealed product. Thus, mechanical properties data for mill-annealed products may have inherent scatter from variations in cold work and values that are not typical of fully annealed material.

In contrast to mill-annealed material, the laboratory annealed condition refers to a "dead soft" or finish annealed product. As will be shown below, some materials that meet ASTM and ASME specifications in the mill-annealed condition have yield strengths after reannealing that fall below current specifications. Practical examples include postweld heat treatments and some final annealing treatments of materials that are worked nonuniformly during fabrication. Assuming that seamless pipe is not used, it is currently planned [1] that the plates to be used in fabricating the Clinch River Breeder Reactor (CRBR) pipes will be reannealed before welding. Furthermore, some pipe bends in the fast flux test facility (FFTF) will also be reannealed [2].

A mechanical properties testing program on liquid-metal fast breeder reactor (LMFBR) structural materials is now under way at Oak Ridge National Laboratory (ORNL). A part of this program includes studies on:
1. product form characterization [3-6] of a single reference of material,

2. heat-to-heat variations [7-8] in tensile and creep properties of 20 heats of type 304 and nine heats of type 316 stainless steel,

3. influence [9] of residual stresses in mill-annealed types 304 and 316 stainless steel on tensile and creep properties,


Work is continuing in the areas listed above, and the objectives of this paper are as follows:

1. report results of yield and ultimate tensile strength determinations on 19 heats of type 304 stainless steel in both mill-annealed (as-received) and reannealed (laboratory annealed) conditions,

2. apply a ratioing technique to define the temperature dependence of tensile properties measured in the ORNL Program.

3. present three different methods of defining minimum strength values.

4. Present average and minimum stress-strain curves (up to 4%) for as-received and reannealed material.

5. demonstrate that when the same methods are used to derive time-independent design stress intensities for Sect. III of the ASME Boiler and Pressure Vessel Code, the ORNL data set leads to different results for reannealed and mill-annealed material.
2. EXPERIMENTAL DETAILS

All 20 heats of the type 304 stainless steel used in this investigation were commercial air-melted heats. They were purchased according to ASTM specifications A 240 for plate A 479 for bar, and A 312 for pipe. Details of heat numbers, vendor, and product form are presented in Table 1. Several product forms of the reference heat [3,4] were also included in the present work. Product forms obtained from the reference heat are summarized in Table 2. The ORNL-determined chemical compositions of these materials are summarized in Table 3.

The test specimens were threaded-end bars having a gage diameter of 6.35 mm (0.250 in.) and a reduced section 31.8 mm (1.25 in.) long. In a few instances a larger specimen having a 57.2-mm (2.25-in.) reduced section was used. All specimens were machined with their major axes parallel to the rolling and/or extrusion directions of the plate, bar, and pipe. The machined specimens were inspected and cleaned, and those receiving a heat-treatment were reannealed at 1065°C (1950°F) for 0.5 hr in argon. The reference heat was reannealed at 1093°C (2000°F) for 0.5 hr, and the grain sizes of all heats were measured in both the mill-annealed and reannealed conditions (see Table 1).

Tensile tests were run on a 44-kN-capacity (10,000-lb) Instron universal testing machine at constant crosshead speeds. Strains measured by extensometers and loads from cells in the load train were obtained for the first 0.05 strain, while crosshead displacement versus load was graphed simultaneously and monitored continuously to rupture. The yield strength values were obtained from the extensometer chart (by the 0.2%
offset method), and ultimate tensile strength was obtained from the load-deflection chart. Most of the tensile data were obtained in the strain range from \(4.17 \times 10^{-4}\) to \(8.33 \times 10^{-4}\)/s.

3. EXPERIMENTAL RESULTS

3.1 YIELD AND ULTIMATE TENSILE STRENGTH DATA ON 20 HEATS OF TYPE 304 STAINLESS STEEL

The 0.2% yield and ultimate tensile strength data \([6,7,13,14]\) are plotted as functions of temperature in Figs. 1 and 2. Figure 1 involves data for as-received (mill-annealed) material, while Fig. 2 shows data for reannealed (laboratory annealed) material for 19 heats. The 20th heat (121) has been excluded from the plots because of its high nitrogen content (0.14%).

3.2 MATHEMATICAL DESCRIPTIONS OF THE DATA

A third-degree polynomial was fit to both yield and ultimate tensile strength data:

\[
S = a_0 + a_1T + a_2T^2 + a_3T^3, \tag{1}
\]

where

\[
S = 0.2\% \text{ yield or ultimate tensile strength},
\]

\[
T = \text{test temperature, } ^\circ\text{C},
\]

\[
a_i = \text{constants}.
\]

The goodness of fit was determined by \(R^2\), the coefficient of determination. \((R^2 = 100\% \text{ means that the model describes the data perfectly.})\)

The constants in Eq. (1) were estimated by the method of least squares. The expected values based on Eq. (1) have been plotted in Figs. 1 and 2. The variability about the expected values is measured by the Standard Error of Estimate (SEE).
The SEE and $R^2$ for yield strength of mill-annealed material (205 data) were 21.1 MPa and 83.8%, respectively, as opposed to 13.6 MPa and 90.41% for the reannealed material (165 data). The SEE and $R^2$ for ultimate tensile strength of mill-annealed material (194 data) were 21.7 MPa and 95.8%, respectively, compared with 24.6 MPa and 94.6% for the reannealed material (155 data). These values show that the variability of yield strength for as-received material is significantly greater than that observed for the reannealed material. However, the variability in ultimate tensile strength for material in the two conditions is more nearly the same.

3.3 APPLICATION OF RATIO-TECHNIQUE TO ORNL DATA

Minimum values for the 0.2% yield and ultimate tensile strengths as functions of temperature available in the *Nuclear Systems Materials Handbook* (NSMH) [15] and for the 0.2% yield strength in ASME Code Case 1592 [16] are based on a ratio technique developed by Smith [17,18]. This technique involves normalizing the data available for a specific material by dividing the elevated-temperature strength values for individual lots by the room-temperature strengths of the same lot, and then establishing a trend curve for these ratios. To obtain the minimum value curves at temperature, the trends observed as ratios were multiplied by the specified room temperature minimum values for the product form, for example, 207 MPa (30 ksi) for plate products [17, 19]. The ORNL data on type 304 stainless steel were subjected to the same ratio technique, and results are presented here.
Figure 3 shows yield and tensile strength ratios as functions of temperature for 19 heats of type 304 stainless steel in the as-received condition. Similar plots for the reannealed condition are shown in Fig. 4. The curves were obtained from equations of the form:

\[ r = 1 + \beta_1 T + \beta_2 T^2 + \beta_3 T^3, \quad (2) \]

where

\[ T = \text{temperature (°C)} - 25, \]

\[ r = \text{ratio of ultimate tensile strength at elevated temperature to ultimate tensile strength at room temperature}. \]

\[ \beta_i = \text{constants}. \]

This equation forces \( r \) to unity at room temperature (25°C).

3.4. MINIMUM VALUE DEFINITIONS

"Minimum" values of yield and ultimate tensile strengths can be defined in various ways. The following three methods will be examined here:

1. Central tolerance limits \( (P = 0.90, \lambda = 0.95) \). These limits mean that at a confidence level of 0.95, 90% of the data are expected to fall between the upper and lower limits, while 5% of the data are expected to fall below the lower bound. These limits are based on the Bonferroni inequality and are discussed by Lieberman and Miller [20].

2. Expected \( -X(\text{SEE}) \) Method. In this method lower limits or minimum values are defined as expected \( -X(\text{SEE}) \), where \( X \) is arbitrarily chosen. Values of \( X = 1.65 \) and 2 have been used frequently, 1.65 more frequently. The minimum values defined as expected \( -1.65\text{SEE} \) and expected \( -2\text{SEE} \) will be compared with the experimental data and the minimum values defined by other methods.
3. Ratio method. The ratio method described in Sect. 3.3 will be used to define minimum values by using Smith [17,18] and ORNL ratios.

The minimum values obtained by these three methods are compared with the mill-annealed data in Fig. 1. Figure 2 compares minimum values calculated by the methods with the reannealed data. The calculation of minimum values by the ratio method requires the knowledge of minimum specified values of yield and ultimate tensile strengths at room temperature. Such specifications for the reannealed material are not available at present. However, a recent paper [9] developed the following relationships for yield and ultimate tensile strengths in the material in the reannealed and as-received conditions:

\[ Y_{RA} = -22.8 \text{ MPa (3.30 ksi)} + 0.922Y_{AR}, \]  
\[ U_{RA} = 17.1 \text{ MPa (2.48 ksi)} + 0.950U_{AR}, \]

where the subscripts RA and AR refer respectively to the reannealed and as-received conditions.

The constants in Eqs. (3) and (4) were estimated from data on 20 heats of type 304 stainless steel over the test temperature range from room temperature to 649°C (1200°F). These equations were used to calculate the minimum expected specified values for the reannealed condition by using the corresponding values for the as-received condition. The minimum specified values of 0.2% yield and ultimate tensile strength obtained by this method for the reannealed condition were 168 MPa (24.4 ksi) and 508 MPa (73.7 ksi), respectively.
The minimum values of yield and ultimate tensile strengths for the reannealed condition in Fig. 2 were obtained by multiplying ORNL ratios by 168 and 508 MPa (24.4 and 73.7 ksi), respectively.

3.5. STRESS-STRAIN BEHAVIOR (UP TO 4% STRAIN)

The monotonic stress-strain behavior (up to 4% strain) of austenitic stainless steel can be described by:

\[ \sigma - \sigma_{PL} = \frac{C\dot{\varepsilon}_p}{1 + \dot{\varepsilon}_p} + \dot{\dot{\varepsilon}}_p, \tag{5} \]

where

- \( C \) = a measure of strength level and, as shown later, related to yield strength
- \( \dot{\dot{\varepsilon}}_p \) = steady-state hardening rate,
- \( P \) = parameter describing the shape of the stress-strain curve before reaching the steady-state hardening,
- \( \sigma_{PL} \) = proportional limit of stress below which there is no plastic strain,
- \( \dot{\varepsilon}_p \) = true plastic strain.

The value \( \sigma_{PL} \) was estimated to be \( 0.5\sigma_y \), where \( 0.5\sigma_y \) is the 0.2% offset yield strength. The constant \( \dot{\dot{\varepsilon}} \) is 2586 MPa, while \( P \) is given by \( 500C \). The value of \( C \) is determined by the criterion that \( \sigma = \sigma_y \) for \( \varepsilon_p = 0.002 \). Since a knowledge of stress and Young's modulus yields the magnitude of the elastic strain, Eq. (5) can be used to calculate the total strain corresponding to a given stress. The analysis of stress-strain behavior is fully described elsewhere [21].

Sikka and Booker [22] and Hammond and Sikka [23] have found excellent agreement between experimental stress-strain curves and those predicted by Eq. (5) for several heats of types 304 and 316 stainless
steel. From this agreement, the model was considered to be reliable and accurate. Therefore, Eq. (5) was used to predict the average and minimum stress-strain curves (up to 4%) for both the mill-annealed and laboratory annealed material. These curves are shown in Fig. 5. The average curves were based on the expected values of yield strength from Figs. 1(a) and 2(a). The minimum stress-strain curves were based on the minimum yield strength values defined as expected $-1.65\text{SEE}$. Stress-strain curves were developed for room temperature and for temperatures from 100 to 700°C in 100°C increments.

4. DISCUSSION

4.1 INFLUENCE OF REANNEALING ON TENSILE PROPERTIES

The average and minimum (expected $-1.65\text{SEE}$) value curves for 0.2% yield and ultimate tensile strength of as-received and reannealed material are plotted in Fig. 6. This figure also includes the Nuclear Systems Materials Handbook minimum value curves. The following observations are applicable to the results presented.

1. The ORNL average reannealed yield strength curve is about 42 MPa (6 ksi) lower than the average as-received curve for the range of test temperatures investigated thus far. The ORNL average reannealed yield strength curve is even slightly below the minimum (expected $-1.65\text{SEE}$) curve for the as-received material. The NSMH curve is not only above (for most of the temperature range) the ORNL minimum curve for the as-received material but also above the ORNL average curve for the laboratory-annealed condition.

2. The NSMH minimum value curve for ultimate tensile strength falls above the ORNL minimum curve (for most of the temperature range) for both the as-received and reannealed conditions.
3. Reannealing affects the ultimate tensile strength much less than it does the yield strength.

Figure 7 compares the 0.2% yield and ultimate tensile strength ratios for the ORNL data with those reported in the literature for as-received material [17,18]. The literature yield strength ratio trend curve is below the ORNL curve, but the ultimate tensile strength curve is higher than both the ORNL as-received and reannealed curves. The small differences between ORNL and literature trend curves for 0.2% yield strength are due to the separate data bases used. The ORNL data were mostly for thick plates, whereas Smith [17,18] used data primarily from bar, pipe-tube, and some plate products. Furthermore, Smith's data are from several testing sources, while ORNL data represent a single source. It should also be noted from Fig. 7(a) that reannealing lowers the yield strength ratio trend curve, even though it has only a small influence on the ultimate tensile strength ratio. The differences between ORNL and literature trend curves for the ultimate tensile strength ratio are probably associated with strain rate differences between the two data sources.

4.2. METALLURGICAL CONSIDERATIONS

Figure 8 shows reannealed grain size measured excluding annealing twins from Table 3 as a function of as-received grain size for 19 heats of type 304 stainless steel. This figure shows that a reannealing treatment of 0.5 hr at 1065°C usually produces no change in grain size, suggesting that the decrease in yield strength on reannealing is brought
about more as a result of recovery and recrystallization processes than grain growth. The greater variation in the yield strength data [Fig. 1(a)] for the as-received material is considered to result from varying amounts of straightening and sizing work present in various product forms and heats investigated [5,9]. The decrease in variation on reannealing possibly occurs as a result of removal of variable work in various product forms and heats by recovery and recrystallization processes.

4.3. COMPARISON OF MINIMUM VALUES

Minimum values obtained by various methods described in Sect. 3.4 are compared with the experimental data in Figs. 1 and 2. These figures show that while all data fall above the minimum values defined by the ratio method at 200°C and below, several data points can fall below the minimum at higher temperatures. This is true for minimum values derived from both the Smith and ORNL ratios for the mill-annealed material and for ORNL ratios for the reannealed material. The ratio method has been used extensively in Code formulation and is easy to apply; however, from this work several weaknesses were apparent:

1. The actual significance of the resultant "minimum" curves is not clear. All data at room temperature must by definition fall above the specified minimum. However, as shown in Figs. 1 and 2, elevated-temperature data can fall below the minimum calculated by the ratio technique.
2. The ratio technique of calculating minimum value curves for yield and ultimate tensile strengths requires the knowledge of specified minimum room-temperature values, which, although available for the as-received condition, may not be available for the reannealed condition.

Among the other two methods, the central tolerance limit method is statistically sound (if its assumptions are met) and clearly states the position of the data between the lower and upper bounds. However, for engineering design applications, minimum values defined by expected $-1.65\text{SEE}$ or $2\text{SEE}$ appear to represent the experimental data well. Figures 1 and 2 show that although expected $-1.65\text{SEE}$ can represent the experimental data well, minimum values defined by expected $-2\text{SEE}$ give additional conservatism. The minimum values defined by expected $-1.65\text{SEE}$ or $2\text{SEE}$ assume a symmetrical variation in data about the expected values. Such an assumption is substantiated by the experimental data in Figs. 1 and 2. The central tolerance limit method, however, produces a flaring effect in the absence or lack of sufficient data at a given temperature, Fig. 1(a) and 2(a). Such a prediction appears inconsistent with the real material behavior. However, the flaring effect observed in the tolerance method results in more conservative values than obtained by the ratio method.

In conclusion, because of less conservative values obtained at elevated temperatures by the ratio method and the inability to represent the real material behavior by the tolerance method, the use of expected $-1.65\text{SEE}$ or $2\text{SEE}$ method of defining minimum values is suggested.
4.4 DETERMINATION OF $S_m$ VALUES

This section deals with the determination of time-independent design stress intensity ($S_m$) values for ORNL data in the mill-annealed and laboratory-annealed conditions. The procedure employed in determining the $S_m$ values is the same as that presented in Appendix A of the back-up document [24] to Code Case 1592.

Figure 9 shows the procedure used in determining $S_m$ values for the ORNL data in as-received and reannealed conditions. The $S_m$ values for as-received material are based on specified room-temperature minimum values of 207 and 517 MPa for 0.2% yield and ultimate tensile strength, respectively. The $S_m$ values for reannealed material were based on specified room-temperature yield and ultimate tensile strength values of 168 and 508 MPa, respectively. The most important quantities in determining the $S_m$ values are the minimum values of yield and ultimate tensile strength. These values are obtained by the ratio method. However, minimum values defined by ratio method have been shown unconservative for describing the experimental data at elevated temperatures, Figs. 1 and 2. Therefore, there may be a need to reassess the current code criterion for estimating the $S_m$ values.

The expected $-2\sigma$ SEE presents an alternative method (Sect. 4.3) of defining the minimum values. The alternate method has already been shown to be superior to the ratio method in representing the real experimental data. We have therefore used this alternative method of defining minimum values with safety factors given in Appendix A of ref. 24 for determining $S_m$ values. In addition this method of defining minimum values did not require a knowledge of specified minimum room-temperature values.
Table 4 summarizes $S_m$ values, computed by the ratio and expected $-2\text{SEE}$ methods, for the ORNL data and compares them with values reported in the Code Case [16,25]. These values are plotted in Fig. 10. The ORNL mill-annealed $S_m$ values computed from minimum values obtained by the ratio method agree well with the current code values. However, the $S_m$ values computed by the alternate method are significantly below the current Code values. For the reannealed material, Fig. 10, $S_m$ values computed by both methods are 24 to 28 MPa below the ORNL as-received values. Furthermore, these figures show that the current Code values are not conservative for the reannealed material for the entire temperature range.

The decrease in $S_m$ values by 24 to 28 MPa on reannealing should significantly affect design stresses in postweld heat-treated areas or on components to be treated to remove the variable cold work introduced during fabrication. It should be noted here that the alternate method proposed in this paper results in more conservative values than currently available in the code [16,25].

4.5 NEED FOR SEPARATE $S_m$ VALUES FOR AS-RECEIVED AND REANNEALED MATERIAL

Nonconservative values of $S_m$ may lead to an accumulation of excessive plastic strain under peak loading conditions. The stress-strain curves in Fig. 5 have been used to determine the average and maximum strain (corresponding to average and minimum yield strength material) values for a stress level of $S_m$. For illustration, we have used the $S_m$ values, derived from ORNL data, using the ratio method. The average
and maximum strains are plotted as functions of temperature in Fig. 11. Figure 11(a) shows results using the $S_m$ values derived from mill-annealed data for both the mill-annealed and reannealed material. Figure 11(b) shows strain values obtained by using $S_m$ values derived from mill-annealed data for the mill-annealed condition and $S_m$ values derived from reannealed data for the reannealed condition. These graphs show the following:

1. When the $S_m$ values derived from mill-annealed data were used to determine strain values for both mill-annealed and reannealed material, the mill-annealed material of average yield strength shows only elastic strains, Fig. 11(a). The elastic strain values exhibit a temperature dependence corresponding to Young's Modulus. However, the reannealed material of average yield strength can develop plastic strains for the same $S_m$ values. For a test temperature range of 200 to 600°C, strains in reannealed material of average yield strength could be 6 to 7 times more than in the mill-annealed material of average yield strength.

   The stress that produces only elastic strain in mill-annealed material of average yield strength can produce significant plastic strains in the mill-annealed material of average yield strength. This observation is true to a lesser degree for mill-annealed than it is for reannealed material. Note, however, that very large strains can result in reannealed material of minimum yield strength when designed to $S_m$ values derived for mill-annealed material.

2. When the $S_m$ values derived from mill-annealed data were used to determine strain values for the mill-annealed material and $S_m$ values derived from reannealed data were used for computing strains in reannealed
material, both the mill-annealed and reannealed materials of average yield strength show elastic strains of essentially the same magnitude. However, even such a use of $S_m$ values can produce significant strains in minimum yield strength materials for both conditions.

Note that the use of $S_m$ values derived from mill-annealed data for mill-annealed material and $S_m$ values derived from reannealed data for reannealed material results in approximately the same magnitude of strains in both mill-annealed and reannealed materials.

Comparison of Fig. 11(a) and (b) clearly illustrates that gross yielding cannot be prevented in reannealed material if current $S_m$ values in the Code Case (which are in good agreement with ORNL as-received $S_m$ values) are used in design for the reannealed material. Therefore, a need exists for either including separate values of $S_m$ for the mill-annealed and reannealed material in the Code or using more conservative reannealed data to set the Code allowable stresses.

5. SUMMARY AND CONCLUSIONS

The 0.2% yield and ultimate tensile strength data for 19 heats of type 304 stainless steel in both the as-received and reannealed conditions have been plotted as functions of temperature to show the effect of reannealing on these properties. Tensile data were also treated in accordance with the ratio technique [17,18]. The minimum value curves for yield and ultimate tensile strength were obtained by different methods and compared with NSMAH minimum curves. Average and minimum stress-strain curves (up to 4%) were developed for both as-received and reannealed material.
The tensile data on 19 heats of type 304 stainless steel in both the as-received and reannealed conditions were used to calculate the time-independent design stress intensity limits, $S_n$. These values were compared with current values in Sect. III [25] and ASME Code Case 1592 [16].

The following conclusions can be drawn:

1. Material in the as-received condition showed larger variations in the 0.2% yield strength than material in the reannealed condition over the temperature range of this investigation (room temperature to 649°C). The SEE in yield strength for as-received material was 21.1 MPa as opposed to 13.6 MPa for the reannealed material. Ultimate tensile strength variations were nearly the same in both as-received and reannealed conditions, SEE of 21.7 and 24.6 MPa, respectively. The large variations in yield strength data for as-received material were associated with varying amounts of straightening and sizing work present in various product forms.

2. Reannealing for 0.5 hr at 1065°C reduced the yield strength over the range from room temperature to 649°C. The reduction was approximately 42 MPa for the whole temperature range and it occurred usually with no change in grain size.

3. Reannealing lowered the ultimate tensile strength by only 7 to 14 MPa.

4. Reannealing lowered the ratio trend curve for yield strength and only slightly influenced that for ultimate tensile strength.
5. The room-temperature minimum expected values of yield and ultimate tensile strengths for reannealed type 304 stainless steel were determined to be 168 and 508 MPa, respectively, rather than values of 207 and 517 MPa currently specified for the as-received material.

6. Three methods of defining minimum values were studied. These methods included: the ratio method, the central tolerance method, and the expected $-1.65\text{SEE}$ or $2\text{SEE}$ method. The expected $-1.65\text{SEE}$ or $2\text{SEE}$ described the variations in the data and the material behavior better than the other two methods. This method generally yields more conservative results than does the ratio method.

7. The $S_m$ values derived from ORNL as-received material data by the ratio technique agreed excellently with those reported in design codes [16,25]. However, analogous $S_m$ values for ORNL reannealed data were 24 to 28 MPa less than the $S_m$ values.

8. The stress-strain curves showed that excessive strains can result in reannealed material if designed to $S_m$ values based on mill-annealed data. Results presented in this report suggest a need for either including separate values of $S_m$ for as-received and reannealed material in the Code or using more conservative reannealed data to set the Code allowable design stresses.

6. ACKNOWLEDGMENT

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7. REFERENCES


[7]. H. E. McCoy, Tensile and Creep Properties of Several Heats of Type 304 Stainless Steel, ORNL/TM-4709 (November 1974).


Table 1. Summary of Vendor, Product Form, and Grain Size of 20 Heats of Type 304 Stainless Steel

<table>
<thead>
<tr>
<th>Heat Symbol</th>
<th>Vendor</th>
<th>As Received Form</th>
<th>Dimension (mm)</th>
<th>Grain Size* (ASTM)</th>
<th>Reannealed (ASTM)</th>
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Table 2. Product Forms of the Reference Heat (9T 2796) of Type 304 Stainless Steel

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Table 3. Summary of Chemical Analysis of 20 Heats of Type 304 Stainless Steel

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Table 4. Summary of $S_m$ Values for Type 304 Stainless Steel from ASME Code and Those Computed for ORNL Data for Mill- and Laboratory-Annealed Material

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<sup>a</sup>Section III Division 1 (Table I.1.2) for temperature ≤427°C and ASME Code Case 1592 (Table I.14.3A) for temperatures ≥427°C.

<sup>b</sup>Specified room-temperature yield and ultimate tensile strengths of 168 and 508 MPa.
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Fig. 1. Strength as a Function of Test Temperature for 19 Heats of Type 304 Stainless Steel in the As-Received Condition. Strain Rates from $4.17 \times 10^{-4}$ to $8.33 \times 10^{-4}$/s. (a) 0.2% yield strength, (b) ultimate tensile strength.

Fig. 2. Strength as a Function of Test Temperature for 19 Heats of Type 304 Stainless Steel in Reannealed Condition. Strain rates from $4.17 \times 10^{-4}$ to $8.33 \times 10^{-4}$/s. (a) 0.2% yield strength, (b) ultimate tensile strength.

Fig. 3. Strength Ratios as a Function of Test Temperature for 19 Heats of Type 304 Stainless Steel in the As-Received Condition. Data are for a single strain rate of $6.67 \times 10^{-4}$/s. (a) Yield strength, (b) ultimate tensile strength.

Fig. 4. Strength Ratios as a Function of Test Temperature for 19 Heats of Type 304 Stainless Steel in the Reannealed Condition. Data are for a single strain rate $6.67 \times 10^{-4}$/s. (a) 0.2% yield strength, (b) ultimate tensile strength.

Fig. 5. Predicted Average and Minimum Stress-Strain Curve for Type 304 Stainless Steel. (a) As-Received, (b) reannealed.

Fig. 6. Comparison of ORNL Average Curves for As-Received and Reannealed Type 304 Stainless Steel with the Nuclear Systems Materials Handbook Minimum Curve. (a) 0.2% yield strength, (b) ultimate tensile.

Fig. 7. Comparison of ORNL Strength Ratios for As-Received and Reannealed Type 304 Stainless Steel with Smith's Curve. (a) 0.2% yield strength, (b) ultimate tensile strength.
Fig. 8. Reannealed Grain Size (Excluding Annealing Twins) as a Function of As-Received Grain Size for 20 ORNL Heats of Type 304 Stainless Steel.

Fig. 9. Determination of $S_m$ Values for ORNL Data on 19 Heats of Type 304 Stainless Steel. (a) Mill annealed, (b) laboratory annealed.

Fig. 10. Comparison of ORNL Mill-Annealed and Laboratory Annealed $S_m$ Values for Type 304 Stainless Steel with Current Code Values. (a) Based on ratio method of minimum values, (b) based on (expected $-2\text{SEE}$) method of minimum values.

Fig. 11. Average and Maximum Strain (for Average and Minimum Yield Strength Material) for Type 304 Stainless Steel in As-Received and Reannealed Conditions. (a) Same $S_m$ values for as-received and reannealed material, (b) separate $S_m$ reannealed material.
Fig. 1. Strength as a Function of Test Temperature for 19 Heats of Type 304 Stainless Steel in the As-Received Condition. Strain Rates from $4.17 \times 10^{-6}$ to $8.33 \times 10^{-6}$/s. (a) 0.2% yield strength, (b) ultimate tensile strength.
Fig. 2. Strength as a Function of Test Temperature for 19 Heats of Type 304 Stainless Steel in Reannealed Condition. Strain rates from $4.17 \times 10^{-6}$ to $8.33 \times 10^{-6}$/s. (a) 0.2% yield strength, (b) ultimate tensile strength.
YIELD STRENGTH RATIO

For a single strain rate of 6.67 x 10^-4/s, the yield strength (a) ultimate tensile strength (b) strength ratio as a function of test temperature for 19 heats of Type 304 Stainless Steel in the as-received condition. Data are

Fig. 3: Strength ratios as a function of test temperature for 19 heats of Type 304 Stainless Steel in the as-received condition.
Tensile strength. A single strain rate of 6.67 x 10^-4 s^-1 (a) 0.2% yield strength, (b) ultimate.

Figure 4. Strength ratios as a function of test temperature for 19 heats of type 304 stainless steel in the remanufactured condition. Data are for a single strain rate of 6.67 x 10^-4 s^-1 (a) 0.2% yield strength, (b) ultimate.
Fig. 5. Predicted Average and Minimum Stress-Strain Curve for Type 304 Stainless Steel. (a) As-Received, (b) reannealed.
Fig. 6. Comparison of ORNL Average Curves for As-Received and Reannealed Type 304 Stainless Steel with the Nuclear Systems Materials Handbook Minimum Curve. (a) 0.2% yield strength, (b) ultimate tensile.
Yield strength, (h) ultimate tensile strength.

Reannealed Type 304 Stainless Steel with Smith's curve. (a) 0.2% yielded strength.

FIG. 7. Comparison of original strength ratios for as-received and reannealed.

Test Temperature (°C)

0.2% Yield Strength Ratio

Ultimate Tensile Strength Ratio
Fig. 8. Reannealed Grain Size (Excluding Annealing Twins) as a Function of As-Received Grain Size for 20 ORNL Heats of Type 304 Stainless Steel.
Fig. 9. Determination of $S_m$ Values for ORNL Data on 19 Heats of Type 304 Stainless Steel. (a) Mill annealed, (b) laboratory annealed.
Fig. 10. Comparison of ORNL Mill-Annealed and Laboratory Annealed $S_m$ Values for Type 304 Stainless Steel with Current Code Values.

(a) Based on ratio method of minimum values, (b) based on (expected -2SEE) method of minimum values.
Fig. 11. Average and Maximum Strain (for Average and Minimum Yield Strength Material) for Type 304 Stainless Steel in As-Received and Reannealed Conditions. (a) Same $S_m$ values for as-received and reannealed material, (b) separate $S_m$ reannealed material.