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SHORT-TIME TENSILE PROPERTIES OF TYPE 316
STAINLESS STEEL FROM $0.6 T_m$ TO $0.9 T_m$

R. H. Marion

MASTER

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TABLE OF CONTENTS

I.	Abstract	2
II.	Introduction	3
III.	Experimental Procedures	3
IV.	Results	5
V.	Discussion	6
VI.	Conclusions	7
VII.	References	8

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SHORT-TIME TENSILE PROPERTIES OF TYPE 316
STAINLESS STEEL FROM $0.6 T_m$ TO $0.9 T_m^*$

R. H. Marion
Ceramics Development Division

ABSTRACT

The mechanical properties of Type 316 stainless steel have been studied at temperatures from 760°C (1400°F) to 1204°C (2200°F) on the Short-Time High Temperature Mechanical Testing Facility. The results demonstrate that reasonable tensile behavior is retained at temperatures approaching the melting point if the strain rate is high enough.

* This work supported by the United States Energy Research & Development Administration.

INTRODUCTION

The analysis of fuel pin failure for fast reactor safety studies requires data on the mechanical properties of austenitic stainless steel at temperatures up to the melting point. There is presently little or no data on these properties at temperatures greater than 871°C (1600°F). The Liquid Metal Fast Breeder Reactor Materials Handbook⁽¹⁾ contains mechanical property data up to 816°C (1500°F) and the only data known to the author at temperatures greater than 871°C (1600°F) are given in references 2 and 3. The need for this information is emphasized by the recent requirement to develop an updated temperature integrity limit for FFTF fuel pins⁽⁴⁾.

In order to obtain information on the very high temperature mechanical properties of austenitic stainless steel, the present study was initiated. The strain rate dependence of the mechanical properties (fracture strength, ductility and modulus) has been examined at temperatures greater than 760°C (1400°F). The results will be compared with information available in the literature.

EXPERIMENTAL PROCEDURES

Tensile test specimens with dimensions given in Fig. 1 were machined from a 15.9 mm (0.63 in) diameter annealed rod of Type 316 stainless steel. Annealed material was chosen for this study in order to eliminate the effects of static recovery and static recrystallization which occur very rapidly at the temperatures to be studied. The test apparatus and the experimental techniques have been described previously^(5,6). All tests were performed in an argon atmosphere obtained in the following manner:

The test chamber was evacuated to a vacuum better than 13.3 Pa (100 μ m Hg), backfilled with 99.995% pure argon, pumped again to better than 13.3 Pa and backfilled with 99.995% pure argon.

The test procedure was as follows: The heating was started by first using RF induction heating on the pull rods (to reduce the temperature gradient along the length of the sample⁽⁵⁾). About 60 seconds later, a high current (low voltage) through the specimen was started and the specimen was heated by self-resistance at 111°C/sec (200°F/sec) under feedback controlled conditions. Specimen temperature was measured with small, fast response chromel-alumel thermocouples. When the specimen attained test temperature, the computer-controlled loading ram, which had been holding the specimen in load control (at zero load to allow free thermal expansion during heatup), switched to loading ram displacement control and performed the test at the desired ram displacement rate.

Tensile tests were performed at strain rates of 0.02/sec and 1/sec. The strain rate was determined from a plot of gage section strain (measured over a 12.7 mm (.50") length) vs time. Although the tests were performed at a constant ram displacement rate instead of a constant strain rate, the strain rate was constant up to necking of the specimen. For the higher strain rate tests, the data were recorded on a Visicorder instead of conventional x-y plotters. Young's Modulus, E, could not be obtained for tests performed at a strain rate of 1/sec because, at this rate, the strain measuring system was too slow.⁽⁶⁾

RESULTS

The experimentally determined ultimate tensile strength (σ_u), 0.2 pct. offset yield strength (σ_y), elastic modulus (E), uniform elongation (ϵ_u) and total ram displacement during loading (d_T) are plotted as a function of temperature in Figures 2-5. Since there is a temperature gradient along the gage length (which is at worst 9 pct), a question arises when defining the temperature. In this report, σ_u and σ_y are plotted vs the maximum specimen temperature (at the center of the gage length) and E , ϵ_u , and d_T are plotted vs the average temperature along the 12.7 mm (.50") gage length used in strain measurement. The modulus actually represents a "loading slope" because at these temperatures it probably will depend on strain rate. However, even at 1168°C (2135°F), there was a definite initial portion of the stress-strain curve which could be represented by a modulus.

One test was run at 966°C (1770°F) with a strain rate of 10^{-4} /sec. The test was stopped at a reduction in area of 35 pct and it had deformed this amount under a stress ≤ 1500 psi. Therefore, it appears that the strength may approach zero at temperatures near 982°C (1800°F) if the strain rate is slow enough. (The creep rate is greater than the imposed strain rate.)

Various measures of the ductility were examined with ϵ_u and d_T (shown in Figures 4 and 5) being representative of the other parameters (post-test sample length, total gage section elongation and reduction in area). In all tests, the reduction in area at fracture was 65-75 pct. It was apparent that there was no drastic loss in ductility with increasing temperature. The ductility decreased slightly as temperature increased for a strain rate of 0.02/sec and remained almost constant for a strain rate of 1/sec.

DISCUSSION

The results on the effect of strain rate on ultimate tensile strength indicate that at 854°C (1570°F) the strength may increase slightly between strain rates of 0.02/sec and 1/sec but at higher temperatures the strength is about the same at the two strain rates. A composite plot of the results presented in this report (with the solid line representing strain rates of 0.02/sec and 1/sec) and literature results at temperatures greater than 871°C (1600°F)^(2,3) on the strength at various strain rates is given in Figure 6 (note that the ref. 3 data is for Type 304L instead of Type 316 stainless steel). It is apparent that at $T \geq 982^\circ\text{C}$ (1800°F) the strength of Type 316 stainless steel probably increases with increasing strain rate but that it remains constant above a strain rate of 10^{-2} /sec.

Literature results on the effects of strain rate on the ultimate tensile strength of annealed Type 304 stainless steel⁽⁷⁾ and 20 pct cold worked Type 316 stainless steel⁽⁸⁾ indicate that between 649°C (1200°F) and 871°C (1600°F) the strength increases with increasing strain rate and becomes constant above a "saturation" strain rate. This "saturation" strain rate (above which the strength is constant) increases with increasing temperature and is approximately 1/sec at 871°C (1600°F). Extrapolation of these results to higher temperatures suggests that the "saturation" strain rate at 982°C (1800°F) will be greater than 1/sec and the "saturation" strain rate at 1093°C (2000°F) will be even greater. However, the results presented in this report demonstrate that at $T \geq 982^\circ\text{C}$ (1800°F) the "saturation" strain rate is less than 10^{-2} /sec. Therefore, the results of references 7 and 8 (on the increase of the "saturation" strain rate with temperature) may not be applicable to extrapolation to higher temperatures.

At the temperatures studied in this work, dynamic recovery and dynamic recrystallization are the controlling factors. Therefore, it is these effects that are really being studied when mechanical testing is performed at temperatures close to the melting point.

The "loading slope" (or modulus) is also dependent on these dynamic processes occurring during the deformation. It is not a true modulus of elasticity but it is the parameter needed to perform calculations for that particular strain rate. The ductility results agree with the conclusions of Moteff et. al.⁽³⁾ who found no significant loss of ductility at temperatures up to $0.9 T_m$.

CONCLUSIONS

The strain rate dependence of the mechanical properties of Type 316 stainless steel has been studied at temperatures from 760°C (1400°F) to 1204°C (2200°F). The results clearly show that reasonable tensile behavior is retained at temperatures approaching the melting point (with no large changes in ductility) if the strain rate is high enough. The data presented should be useful in fast reactor safety analyses.

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NOTES

1. ALL DIAMETERS MUST BE TRUE AND CONCENTRIC TO WITHIN 0.0005 INCH
2. BOTH ENDS FLAT AND PERPENDICULAR TO WITHIN 0.0005 INCH
3. DO NOT UNDER CUT RADII AT TANGENT POINTS
4. ALL DIMENSIONS ARE IN INCHES. TOLERANCES ARE ± 0.001 INCH ON DIAMETERS, ± 0.005 INCH ON LENGTHS

Fig. 1. Tensile test specimen.

Figure 2. Ultimate tensile strength (σ_u) and 0.2 pct offset yield strength (σ_y) versus temperature for type 316 stainless steel.

Figure 3. Young's Modulus (E) versus temperature for Type 316 stainless steel.

Figure 4. Uniform elongation (ϵ_u) and total ram displacement during loading (d_T) versus temperature for a strain rate of 0.02/sec for Type 316 stainless steel.

Figure 5. Uniform elongation (ϵ_u) and total ram displacement (d_T) versus temperature for a strain rate of 1/sec for Type 316 stainless steel.

Figure 6. Comparison of the ultimate tensile strength (σ_u) versus temperature with the results of other investigators.

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