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EFFECT OF STRAIN RATE
ON MECHANICAL PROPERTIES
OF AUSTENITIC STAINLESS STEELS

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EFFECT OF STRAIN RATE ON MECHANICAL PROPERTIES
OF AUSTENITIC STAINLESS STEELS

By

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ABSTRACT

A literature survey of high strain rate effects on the mechanical properties of austenitic stainless steels applicable to fast reactor technology showed little information available. Two general tentative observations were that (1) the flow stress of austenitic stainless steels is more strain rate sensitive above 1000 °F than below, and (2) ductility parameters are reduced at low temperatures by increasing the strain rate while, at high temperature, the opposite might be true.

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EFFECT OF STRAIN RATE ON MECHANICAL PROPERTIES
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INTRODUCTION

Results of a survey seeking information on the strain rate sensitive behavior of austenitic stainless steels applicable to fast reactor technology are reported herein. The search for this information was made with two problem areas particularly in mind. These problem areas concern the behavior of the large containment vessel and top cover during impact from within, and the behavior of core structure under conditions of thermal pulse and/or rapid loading. To assess structural behavior under such conditions for the purpose of evaluating potential design deficiencies, mechanical properties data on austenitic stainless steels are needed in the temperature range of 500 °F (260 °C) to 1400 °F (760 °C) at strain rates of approximately 0.01 sec^{-1} to 100 sec^{-1} or possibly higher. The greatest emphasis from the standpoint of FFTF construction is currently placed on the austenitic stainless steels of the 304 and 316 types. An important consideration is the possible deleterious effects on the high strain rate behavior of these materials due to irradiation damage by neutron fluences as high as $5 \times 10^{23} \text{ n/cm}^2$.

Two general aspects involved in the response of metals to high velocity deformation are inseparable in evaluating the integrity of a structure under conditions of rapid loading. The first is the influence of strain rate or time on the stress-strain relationship. This effect, well known to metallurgists, is demonstrated by the fact that the results obtained in a simple tension test depend, for most metals, on the speed at which the testing machine is operated.

The second general aspect of high velocity deformation is the phenomenon of wave propagation. Strain (or stress) waves become significant when the acceleration of an element of volume of the material is of such a magnitude that the inertia forces in the element become comparable to the flow stress forces. A great variety and complexity of propagating strain waves may be developed, depending upon the manner of applying external loads, the size and shape of the piece of metal, and the generalized stress-strain to strain rate relation for the material. In other words, the mechanical behavior of the metal becomes sensitive to its geometry as the straining velocity increases.

This report discusses both aspects of the high strain rate behavior of austenitic stainless steels and, therefore, is separated into two sections. The first section presents the results of a literature survey of material behavior. The second section describes, in greater detail, some of the complexities in data analysis which develop at high strain rates.

SUMMARY AND CONCLUSIONS

A survey of the literature indicated available data on the effect of strain rate on flow properties of austenitic stainless steel to be relatively limited. Much of the available data were obtained more with the intent to evaluate or demonstrate a test technique than to study a materials behavior. It should be noted that no information on the strain rate sensitivity of austenitic stainless steels irradiated to high fluences ($>10^{21}$ n/cm²) could be found. Furthermore, for the two alloys of particular interest, annealed 304 and 316 SS, no data could be found for either the temperature or the strain rate ranges identified for FFTF application.

Consideration was also given to the manner in which non-uniform stresses may develop in a rapidly loaded body. The

simple example discussed was a uniform rod rigidly fixed at one end, and the other end given an axial velocity.

The essential conclusions obtained in this study can be summarized as follows:

- The flow stress of several annealed stainless steels is more strain rate sensitive above $T_m/2$ (1030 °F) than below. This condition may indicate that the rate controlling deformation process changes in the vicinity of $T_m/2$. At strain rates above approximately 100 sec^{-1} , the boundary between low and high rate sensitivity appears to shift to a lower temperature. This behavior is schematized in Figure 1.
- A very limited amount of data indicates that ductility parameters below about 550 °F are reduced by increasing strain rate, while the opposite is true at higher temperatures. Cold working may promote reduced ductility at both higher temperatures and higher strain rates.
- According to the data of Martin and Weir, obtained at strain rates below $3 \times 10^{-2} \text{ sec}^{-1}$, irradiation does not significantly alter these conclusions. It should be recognized that this insensitivity to neutron fluence may not be obeyed at higher strain rates.
- For complex geometries composed of rate sensitive materials, a realistic incorporation of mechanical behavior data into an analysis of the high velocity mechanical behavior of the structure may require difficult numerical calculations and/or an experimental evaluation of sub-scale model behavior.

FIGURE 1. *Schematic Interpretation of Rate Sensitive Nature of Stainless Steel Flow Stress*

SURVEY OF THE LITERATURE

In general, the amount of information concerning the high strain rate behavior of austenitic stainless steels is quite limited. Much of the available data were obtained more with the intent to evaluate or demonstrate a test technique rather than to study a material behavior. In particular, no data on the high strain rate behavior of austenitic steels irradiated in a fast reactor to very high fluence levels could be found. Perhaps the most relevant information currently existing is that obtained by Martin and Weir⁽¹⁾ on annealed 304 and 347 SS. The data, although obtained at relatively low strain rates, did evaluate a strain rate behavior on subsize tensile specimens irradiated at temperatures from 340 °F (170 °C) to 1300 °F (704 °C) and tested at temperatures from room temperature to 1560 °F (850 °C). The irradiations were conducted in the ORR to a fluence level of approximately 7×10^{20} n/cm² (E > 1 MeV),

and the strain rates were varied from $3.3 \times 10^{-5} \text{ sec}^{-1}$ to $3.3 \times 10^{-2} \text{ sec}^{-1}$.* The flow properties of 304 SS were observed to be strain rate insensitive** in either the unirradiated or irradiated conditions below a test temperature of about $T_m/2$ (1030 °F). Above this temperature and for this range of strain rates, the flow properties become more rate sensitive although neither fluence nor irradiation temperature affect the rate sensitivity. At 1550 °F (843 °C), the yield strength is unaffected in going from a strain rate of $3.3 \times 10^{-5} \text{ sec}$ to $3.3 \times 10^{-2} \text{ sec}^{-1}$, while increase in the true ultimate strength by approximately 2.5 indicates a significant dependence of strain hardening on strain rate in this temperature range. At room temperature, Martin and Weir found that the ductility, in terms of uniform elongation, was reduced with increasing strain rate. However, the ductility parameter was insensitive to strain rate at 750 °F (400 °C) and increased with strain rate at 1550 °F (843 °C). This latter effect is consistent with the interpretation that, at high temperatures, the fracture mode of stainless steels occurs primarily by grain boundary decohesion. Because formation of critical size grain boundary cracks is believed to be diffusion controlled, the time under stress would control the ductility.

Hauser⁽²⁾ has measured the room temperature flow stress behavior of annealed Type 304 SS in the strain rate range of from $1 \times 10^{-4} \text{ sec}^{-1}$ to $1 \times 10^3 \text{ sec}^{-1}$. Results of these data, shown in Figure 2 indicate a moderate rate sensitivity in the flow stress. The flow stress becomes more rate sensitive above strain rates of about 10 sec^{-1} . The data, obtained from a

* For consistency, all strain rates are given in this report in terms of sec^{-1} .

** Strain rate sensitivity as discussed in this report refers to the degree of response of the change in parameter (flow stress, ductility, etc.) due to a change in strain rate. Mathematically, it may be referred to as $\frac{\partial \ln \tau}{\partial \ln \dot{\epsilon}}$ or $\frac{\partial \ln \tau}{\partial \epsilon}$.

FIGURE 2. Effect of Stress on Strain Rate at Constant Strain for Stainless Steel, Showing Sampling of Experimental Record

Hopkinson bar-bar impact machine, is described by Hauser in his paper. The Hopkinson technique, or the various modifications of it, is the most typical method of determining flow stress behavior in the strain rate range of 50 sec^{-1} to 2000 sec^{-1} . No ductility information is directly available from this type of test as the specimens are loaded in compression.

Strain rate has also been found to indirectly affect the amount of martensite formed during straining in metastable austenitic stainless steel. Bressanelli and Moskowitz⁽³⁾ found that, in Type 301 SS, an increase in the strain rate causes a reduction in the amount of martensite formed at any given strain level. They found this effect attributable to adiabatic heating during plastic straining. A reduction in martensite formation during straining was found to decrease ultimate strength and elongation. Increasing the alloy content increases the austenite stability as evidenced by a lowering of the M_d temperature. Above the M_d temperature, of course, this phenomenon is unimportant. Some earlier work by Form and Baldwin⁽⁴⁾ was also intended to evaluate the significance of strain rate and temperature on martensite formation in Type 303 and 310 SS. Their results, while not fully accounting for the observed behavior, are interpretable in terms of the explanation offered by Bressanelli and Moskowitz. The test results of Form and Baldwin, although presented only in terms of the natural logarithm of the ratio of original area to the final areas, are of interest here because of the wide range of temperatures and strain rates employed. The results for Type 303 SS and Type 310 SS are shown in Figures 3 and 4, respectively. In these figures, the strain rates are given in terms of min^{-1} and must be multiplied by 1.67×10^{-2} to convert to sec^{-1} . Both types of steels show similar ductility behavior. At slow rates ($<10^{-1} \text{ sec}^{-1}$), a maximum in ductility occurs at

FIGURE 3. Ductility of AISI 303 SS as a Function of Strain Rate and Test Temperature

FIGURE 4. Ductility of AISI 310 SS as a Function of Strain Rate and Test Temperature

approximately room temperature, while at strain rates of about 20 sec^{-1} (10^3 min^{-1}) and above the ductility increases monotonically with increasing temperature.

Some additional test data on Type 301 SS at temperatures from 1600°F (870°C) to 2240°F (1230°C) have been obtained by Roe and Kattus.⁽⁵⁾ This work, shown in Figures 5 and 6 indicates a quite large rate sensitivity in the flow stress at these high temperatures. The ductility is also fairly strain rate sensitive and increases with increasing strain rate. This data contrasts the room temperature behavior where, for example, Moon and Campbell⁽⁶⁾ show only a 15% increase in the ultimate strength of Type 301 SS for a change from static to rates of 1 sec^{-1} . In the case of Type 302 SS, Clark and Wood⁽⁷⁾ found a 19% increase in ultimate tensile strength in going from static rates to approximately 100 sec^{-1} .

At strain rates of the order of 10^3 sec^{-1} , Type 304 SS has been found to become fairly rate sensitive even at room temperature, as has been demonstrated by Johnson et al.⁽⁸⁾ The fact that this material becomes more rate sensitive at high strain rates is also suggested by Hauser's data in Figure 2. A comparison of the static and dynamic stress-strain relation obtained by Johnson et al. is shown in Figure 7. The dynamic data were obtained from an exploding ring test in which the specimen material was machined into a ring and then pressed onto a cylindrical core. The cylindrical core had a high explosive packed into a hole along its axis. After detonation, the ring trapped a portion of the compressive shock wave emanating from the center of the core, and its progressive expansion was monitored by high speed photography. In their tests on the Type 304 SS, plastic strain rates of approximately $4.5 \times 10^3 \text{ sec}^{-1}$ were obtained. This test technique appears to have an advantage of stressing the entire specimen uniformly. In the more conventional shock tests, a rod of the test material

FIGURE 5. Temperature Effect After 1800-sec Hold Time on 0.2% Offset Yield and Ultimate Tensile Strength of Full-Hard 301 SS Sheet at Different Strain Rates (Specimens heated to test temperature in 10 sec)

FIGURE 6. Temperature Effect After 1800-sec Hold Time on Percent Elongation and Modulus of Elasticity of Full-Hard 301 SS Sheet at Different Strain Rates (Specimens heated to test temperatures within 10 sec)

FIGURE 7. Stress-Strain Results for Type 304 SS at Room Temperature

shocked at one end stresses the material by means of a shock wave propagating down the length of the rod.

Test results on cold worked Type 304 SS at temperatures of 74 °F (23 °C) and 900 °F (482 °C) in the strain rate range of 10^{-5} to 10^2 sec^{-1} steel have been provided by Jackson.⁽⁹⁾ These data, shown in Figures 8 and 9, differ distinctly in several respects from the results described previously. First, the flow stress becomes less rate sensitive at higher strain rates. Secondly, in this temperature range, the rate sensitivity does not increase significantly (if at all) with increasing temperature. Finally, total elongation decreases at 900 °F with increasing strain rate as it does at room temperature. While this latter point differs from the results of Martin and Weir, and Form and Baldwin, the comparison may not be strictly valid because of differences in the method of measuring ductility. However, based on these limited results, cold working appears to alter the strain rate behavior of Type 304 SS significantly.

DEFORMATION BEHAVIOR UNDER DYNAMIC CONDITIONS

The statement that a force suddenly applied to a body is not instantaneously transmitted to the remote portions of the body, while quite obvious, implies a mode of behavior which may be extremely complex. The disturbances produced by the force may separate into several components or waves, with each propagating through the body at different speeds depending on the elastic constants and the stress plastic strain relation. One of the more elementary problems of wave propagation in solids is the propagation of a longitudinal wave in a slender rod. This problem will be considered here not only for its simplicity but also because it demonstrates some of the behavior common to more complex geometries and loading conditions.

Consider first an infinitesimal element of volume in a rod shown in Figure 10. If we suppose the longitudinal stress

FIGURE 8. Effect of Strain Rate on Yield and Ultimate Tensile Strength of Cold Worked 304 SS

FIGURE 9. Effect of Strain Rate on Ductility of Cold Worked 304 SS

FIGURE 10. *Schematic of Cylindrical Rod Subjected to Rapid Elongation*

on one side to be slightly greater by an amount $(\partial\sigma_x/\partial x)dx$, then the net force on the element is simply $A(\partial\sigma_x/\partial x)dx$, where A is the cross-sectional area. In time t , the element will displace a distance u and we may write the net initial force on the element as

$$dm \frac{\partial^2 u}{\partial t^2} = A \frac{\partial \sigma_x}{\partial x} dx \quad (1)$$

where dm is mass of the element and is given by $\rho A dx$ (ρ = density). Substituting for dm , Equation (1) becomes,

$$\rho \frac{\partial^2 u}{\partial t^2} = \frac{\partial \sigma_x}{\partial x} \quad (2)$$

If the deformation is purely elastic,

$$\sigma_x = E e_x = E \frac{\partial u}{\partial x}$$

Eliminating σ_x from Equation (2) gives the wave equation

$$\frac{\delta^2 u}{\delta t^2} = \frac{E}{\rho} \frac{\delta^2 u}{\delta x^2} .$$

The solution to this equation represents a wave propagation along the x-axis with speed, c_o , equal to $\sqrt{E/\rho}$. Armed with this information, we may now consider the situation in which a rod is rigidly fixed at one end and the other end suddenly acquires a constant velocity, v . To further simplify this example, we will assume that the material has a constant rate of strain hardening, $\theta = d\sigma/d\epsilon_p$, beyond yield point. This latter assumption provides a constant propagation velocity to the plastic portion of the wave since, from the von Karman⁽¹⁰⁾ theory, the plastic wave velocity is given by

$$C_p = \sqrt{(1/\rho) (d\sigma/d\epsilon_p)} = \sqrt{\theta/P} .$$

Now, the sudden increase in velocity of the free end produces a stress at the end, and it may be shown from the impulse-momentum principle that this stress is

$$\sigma = \rho C \Delta v \quad (3)$$

with Δv the velocity change in any element of volume. This is known as the particle velocity. In the case of Type 304 SS where $E = 28 \times 10^6$ psi and $C_o = 2 \times 10^5$ ips, the v required to attain a stress of 30,000 psi (approximate yield strength) is about 16 fps (192 ips). First, examine the case where V is such that $\sigma = \sigma_y/2$. Then a purely elastic wave propagating towards the fixed end will be generated. The stresses ahead of the wave are zero and the material is at rest. Behind the wave, the stress is $\sigma_y/2$ and the particle velocity is $v = \sigma_y/2\rho C_o$. After time $t = L/C_o$, where L = bar length, the wave reaches the fixed end. Since the bar is rigidly mounted, the particle velocity must be zero at the fixed end and, therefore, the particle velocity behind the wave must change to zero when the wave reaches this location. This condition is

satisfied by the superposition of a second wave whose propagation and particle velocity are of equal magnitude but in the opposite direction. Adding this wave to the original wave yields a wave propagating back toward the face end with speed C_0 , amplitude σ_y , and a net particle velocity of zero behind it. Upon reaching the free end, another wave is superimposed due to the constant velocity of the free end. However, the increased stress associated with this third wave results in a total stress in the plastic range, and so the stress increment is smaller and is expressed by $\Delta\sigma = v_p C_p$, giving a total stress of $\sigma_y + \Delta\sigma$. This plastic wave continues the process except at a slower rate. The stress is increased at each end until fracture occurs. It is interesting to note that fracture will always occur at one of the ends if the bar is homogeneous.

If the velocity of the free end is greater than that required to initiate yielding, then a different distribution of plastic strains is likely. For example, consider the case in which $v > \sigma_y / \rho C_0$. Both a plastic and an elastic wave are generated. The magnitude of the elastic wave is σ_y , and the magnitude of the plastic wave can be obtained from the displacement at the free end. This displacement is composed of an elastic and a plastic term

$$vt = \delta_e + \delta_p \quad (4)$$

In time t , the elastic wave has travelled $C_0 t$ down the bar and the plastic wave has travelled $C_p t$ so the average elastic strain $= e = \delta_e / C_0 t = \sigma_x / E$ and the average plastic strain $= E_p = \delta_p / C_p t = (\sigma - \sigma_x) / \theta$. Substituting into Equation (4) and solving for the plastic stress increment gives

$$\sigma - \sigma_y = \frac{\theta}{C_p} V - \frac{\delta_y C_0}{E}$$

This plastic wave propagates more slowly than the elastic wave ($C_o > C_p$) and the particle velocity associated with it is a fraction of the total velocity of the end of the bar. The remaining portion of the total velocity is associated with the elastic wave which, in this case, is $\sigma_y/\rho C_o$. The fact that the particle velocity of the elastic wave must go to zero upon reaching the fixed end means that the stress at the fixed end will be increased by an amount of $C_p \sigma_y/C_o$. If this additional stress causes fracture, an elastic wave unloading the bar will return from the broken end. This unloading wave will reach the plastic wave after it has progressed a distance of $2C_p L/C_p + C_o$. It is likely, then, that the stresses associated with the plastic wave will be reduced below σ_y . The net result in this imaginary experiment is that of a bar plastically deformed over only a fraction of its length but whose fracture strength is exceeded.

If we were to consider the more realistic case where $\theta = \theta(\epsilon_p)$ and $\sigma = \sigma(\dot{\epsilon})$, the analysis would become considerably more difficult. The problem, in fact, could not be solved in closed form even for a simple geometry as a slender rod. For complex geometries composed of strain rate sensitive materials, a realistic incorporation of materials data into an analysis of the high velocity mechanical behavior of the structure would require a rather difficult and complex numerical calculation and/or an experimental evaluation of sub-scale model behavior.

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