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Tensile Instability and Deformation Behavior of Rapidly Heated Metals in a Constant-Load Environment[1]

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The deformation and failure of rapidly heated metals under constant-load conditions are an area of mechanics in which there has been little research. This is due in part to the experimental challenges involved in the creation of rapid temperature rises in a tensile test specimen and in producing the high strain rates necessary for maintaining a constant load. Additionally, there are the instrumentation problems associated with the measurement of the transient deformation and temperature changes of a metal subjected to this thermomechanical history. This paper focuses on the tensile deformation behavior of metals when rapidly heated (of the order of $100\ \mathrm{K \cdot s^{-1}}$) by the passage of an electric current while a constant load is maintained by a servohydraulic actuator. Experimental observations on the deformation behavior of several metals are presented. The three competing processes, work hardening, annealing, and reduction in cross-sectional area, involved in the development of a tensile instability are examined and are related to the characteristics of the loading system and the temperature rise rate.

KEY WORDS: high strain rate; high temperatures; mechanical properties; metals; rapid heating; tensile instability.

1. INTRODUCTION

Of the various methods that have been developed to characterize the mechanical behavior of materials there are relatively few that address conditions outside that of an isothermal environment. There are, however, some engineering problems where the primary variable is temperature. In order to make a rational analysis of the structural consequences of the

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rapid heating of a load bearing component, it is necessary to develop measures of the mechanical behavior of materials beyond the range of thermal expansion and yielding, up to and including the point of failure, with which useful predictions on performance can be made.

In most standard elevated temperature mechanical property tests great effort is expended to ensure a constant and uniform temperature in a material while it is pulled, squeezed, bent, or twisted. Once a constant temperature is achieved the mechanical behavior is often measured while the load, loading rate, stress, or strain rate is held constant. While these thermomechanical environmental conditions may be useful for the comparison of materials, or the verification of a constitutive relationship that may describe the mechanical behavior under these special conditions, they are seldom directly applicable to the real world of variable temperature and load that most structures must function in.

For the work described in this paper, only one variable is held constant, that of the load on the test specimen. The temperature of the material is increased rapidly until tensile failure occurs. The deformation of the material progresses from thermoelastic effects (thermal expansion and modulus change) through yielding, to plastic deformation at high strain rates near failure. The elongation of the tensile test specimen is measured up to the point of failure, as are the load and temperature histories.

Earlier work on this particular thermomechanical history was done at the Naval Ordnance Test Station (now called the Naval Weapons Center, China Lake) in the 1950s by W. K. Smith and A. T. Robinson [1]. Their interest was in the mechanical behavior of rapidly heated metals in a constant-load environment up to the yield temperature which limited the maximum plastic strain to 0.002. This strain was within the short time stroke capacity of the modified deadweight-loaded creep test machines they used to stress their test specimens.

In contrast, the most closely related isothermal test is the creep rupture test, where a load is applied to a tensile test specimen at elevated temperature and the deformation is measured with respect to time up to failure. This is a static environmental situation, where the microstructure of the metal does not change much for the duration of the test, and the strain rate is slow and essentially constant for most of the time, except as tensile instability is approached.

The servohydraulic test machine used in the work reported here has a much greater range of stroke than a creep test machine and allows the behavior of a tensile test specimen to be studied at large strains and high strain rates. It is shown that a stressed metal subjected to rapid heating responds by deforming and work hardening so that a stable load can be supported well after yielding to several percent of strain.

2. EXPERIMENTAL METHODS

To measure the mechanical properties of a solid it is necessary to create a volume of material in which both the temperature and the stress are uniform. In an isothermal environment the first requirement is easy to achieve by simply waiting long enough, and the second is dependent only on the gripping scheme employed for applying force to the test specimen.

Our interest, however, is in the mechanical behavior of a stressed metal when it is heated rapidly. Most of the experimental techniques utilized for determining the elevated temperature behavior of materials are not applicable to this problem. The furnaces typically used for elevated temperature tests of metals are capable of only very slow temperature rise rates. Even if one had a furnace capable of rapid heating, there would still be the problem of steep temperature gradients from the surface to the interior of the test specimen.

What is required is a volumetric method to heat the metal rapidly. This can be achieved by passing sufficient electric current through the material. This direct resistance heating method has been used quite often in the past by several investigators [1, 2] to produce a rapid and fairly uniform temperature rise in a sample of material large enough for convenient instrumentation and measurements.

By making the tensile test specimen of sufficient length there will be a region about the center in which the temperature does not vary much along the length. Near the ends there will be temperature gradients resulting from heat being conducted into the cooler grips. A center-to-surface temperature gradient will also exist in the test specimen because of heat loss by radiation and convection, but this can be minimized by using thin test specimens.

To create the desired temperature history in a reasonably sized tensile test specimen, a spot welder transformer was utilized. This type of transformer has a secondary winding consisting of a single loop of a heavy copper conductor and can easily supply several thousand amps of current. An autotransformer (Variac) was connected to the primary side of this transformer to provide control over the current output. A large selenoid switch was inserted between the autotransformer and the primary of the spot welder transformer to provide an on–off control. This switch was in turn energized by a 24-V relay which could be connected to a remote switch or a computer. Figure 1 shows a block diagram of the major components of the power supply.

This power supply was applied to a 44.48-kN-capacity servohydraulic load frame with an insulated load train as shown in Fig. 2. The specimen space was isolated by the load train insulators. The specimen and the loop

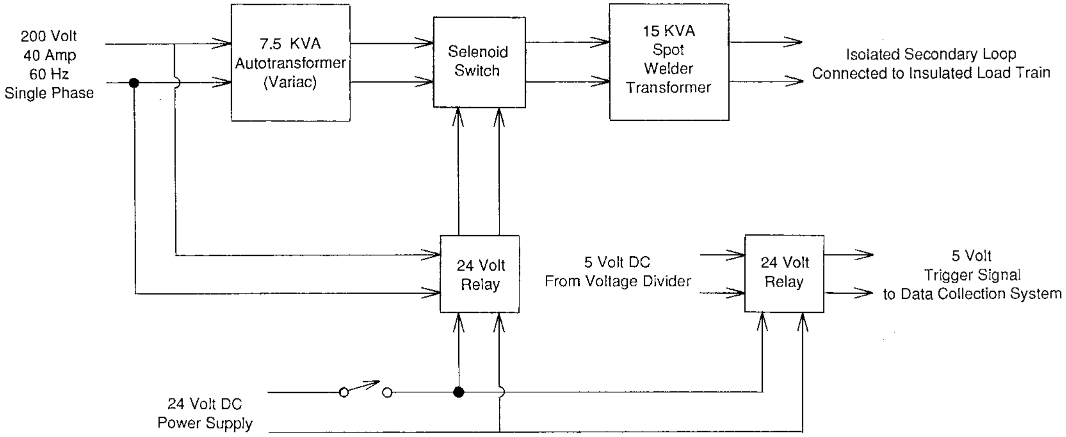

Fig. 1. Block diagram showing the major components of the power supply used to heat the test specimens. The current is turned on by a switch that controls two relays. One relay energizes a selenoid switch that connects the autotransformer to the spot-welder transformer, which in turn induces a high current in the isolated loop through the insulated load train. The other relay is used to generate a 5-V signal for triggering the data collection system.

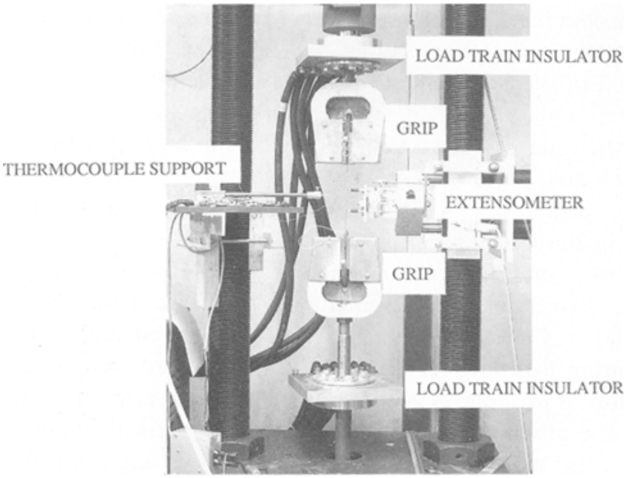

Fig. 2. Photograph showing the insulated load train installed in a 44.48-kN-capacity servohydraulic load frame. The grips pointed out are of the wedge type with file face inserts. Also shown are the extensometer and the thermocouple probe support.

through the transformer were not grounded, but floated electrically with respect to the surroundings. The grips used to apply force to the test specimen were of the wedge type with file face inserts. This limited the test specimen configuration to flat strips, but since most of the metals studied were available only in sheet form this was not a problem.

An additional advantage in using sheet metal is that the tensile test specimen configuration was nothing more than a low-cost sheared strip. For a normal tensile test specimen it is necessary to machine a reduced section in a sample of the material to avoid fracture in the grips. With materials in sheet form this is an expensive operation. Since the gripped portion of a strip of metal heated by an electric current is much cooler than the central region, this reduced section, or "dogbone" configuration, is not required to avoid fracture in the grips.

The characteristics of a servohydraulic load frame allow the movement of the actuator to be controlled to produce whatever condition in the test specimen that is required, be it a certain load, strain, or displacement, depending on the transducer selected for the control feedback. There are limits on the response of these test machines that are related to the servovalve design, the volume capacity of the hydraulic power supply, and the control electronics. The servohydraulic system (Instron, Series 2150) used had an adequate response for the temperature rise rates that could be produced with the power supply utilized for specimen heating.

The mechanical boundary condition selected for these experiments was to maintain the load at some set level. The servohydraulic test machine was programmed in the load control mode with sufficiently high gain for good response, but low enough to avoid instabilities from the electronic interference in the load cell circuit produced by the high currents used to heat the test specimen. At low loads, where a high gain had to be used with the load cell to generate a control signal for feedback, there were problems with noise in the load history.

Elongation in the test specimen was monitored with two different transducers. For direct measurement of the strain a modified quartz rod extensometer was used. The quartz arms of this extensometer were replaced with aluminum extensions because of a fracture problem with the original configuration. Short pieces of the original quartz arms were inserted into the end of the aluminum extensions for contact with the test specimen.

The second method was to use the displacement transducer that was incorporated into the servohydraulic actuator. While displacement of the ram included thermal expansion of the grips and other parts of the load train, it was found that this was a useful way to measure the deformation of materials that exceeded the range of the extensometer.

Temperature measurements were made using conventional thermocouple techniques. Type K (chromel–alumnel) thermocouples with a 0.0254-mm wire diameter were chosen as a good compromise between response and ease of handling. The primary challenge with temperature measurement was the thermocouple attachment method. For many metals the spot welding technique worked well. Despite the fact that the thermocouple was attached to a conductor carrying an AC current, this had little effect on its output if the signal was properly filtered. The two wires were welded onto the test specimen without a bead, using the test material as an intermediate metal. Care was taken to ensure that the two attachment points were on the same plane across the test specimen to minimize the effect of voltage drop between them.

For some metals, such as aluminum, the spot-welding attachment method does not work well. It was difficult to get a mechanically sound weld when trying to spot weld a nickel-base alloy to aluminum. The temperature measurement method developed for aluminum alloys was to use a “strap” thermocouple where the wires are pulled against the edges of the test specimen. This is an intermediate metal thermocouple, as was the case for the spot-welded attachment method discussed above.

The problem with this scheme is that the temperature is being sensed from the specimen edge, which is cooler than the rest of the specimen due to the accelerated heat loss in the corner region. In addition, there is the intrinsic error introduced by the heat being conducted away from the measurement point by the wires. However, given the choice between no measurement at all due to detachment and the measurement taken from the edges, the latter was chosen.

To evaluate the magnitude of the temperature measurement error, a trial was conducted with a twin-strip type of tensile test specimen fabricated from aluminum with a thermocouple sandwiched in between the two strips. This design was used by J. A. Van Echo [3] for evaluating the short time creep of metals. A strap type of thermocouple was also applied to the same test specimen. Comparison of the temperatures measured when this was heated rapidly showed little difference between the two techniques.

A DEC MINC-23 modular instrument computer was used to record the results of an experiment. An interpreted language (Basic) was used for programming, which limited the maximum sampling rate to 40 Hz. This was adequate for most of the experiments but limited the temperature rise rates that could be studied. The thermocouple amplifier in the computer was an isolated chopper type and used a three-pole filter with a 60-db/decade rolloff to attenuate the 60-Hz noise picked up from the heating current. Three channels of information were recorded for a test. These were temperature, load, and strain.

3. EXPERIMENTAL OBSERVATIONS

A typical strain vs load record for the isothermal deformation of a metal will have elastic deformation up to some limit (yield), after which the deformation is primarily plastic. Continued deformation will result in increasing loads until a tensile instability occurs, and the load sustained by the tensile test specimen starts to drop. Fracture then occurs shortly after this condition is achieved, if the test is conducted in a load control environment.

To investigate the mechanical behavior of rapidly heated metals in a constant-load environment, a tensile test specimen is loaded to a point on its isothermal strain vs load curve. This is the initial part of the thermomechanical history of the metal beyond that of its manufacturing processing. After this condition has been established, an alternating (60-Hz) electric current is sent through the test specimen to heat it. As shown in Fig. 3, which is a strain record for a cold rolled low-carbon steel stressed to 81.2 MPa, the initial displacements observed are due to thermal expansion and elastic modulus change. The yield point is defined as a 0.002 strain offset from the linear portion of the record. Above the yield temperature plastic deformation becomes the dominant contribution to the strain record.

As the temperature of the metal increases beyond the yield

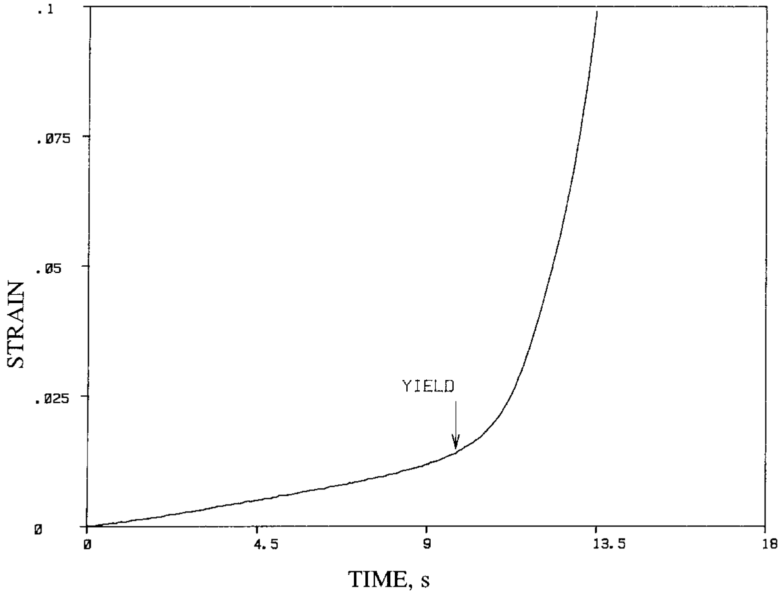

Fig. 3. Strain history for a 19.05 × 0.66-mm sample of a cold rolled low-carbon steel (AISI 1010) after being initially stressed to 81.2 MPa and heated at approximately 60 K · s^{-1}. The initial part of the deformation up to the yield temperature is due to thermoelastic effects. After the yield temperature plastic deformation becomes the dominant contribution to the strain record.

temperature, the rate of deformation accelerates as the servohydraulic actuator attempts to maintain the original load. The deformation causes a reduction in cross-sectional area and a corresponding increase in stress. Finally, a point is reached at which a tensile instability occurs, and the load sustained by the test specimen starts to drop. A local reduction in cross-sectional area forms in the test specimen, which increases the current density and heating rate at that point. The temperature along the length of the specimen is no longer uniform and fracture follows shortly after this event.

The load and temperature histories associated with the strain history discussed above are shown in Figs. 4 and 5, respectively. The load sustained by the test specimen, as shown in Fig. 4, remains fairly constant over a considerable range of plastic deformation. The irregularities in the load record are due to electronic interference. The time at which the load just starts to drop denotes the development of a tensile instability in the test specimen. The temperature history for this test is virtually linear at the lower temperatures, with the rise rate being reduced as heat loss from radiation becomes important at the higher temperatures as shown in Fig. 5.

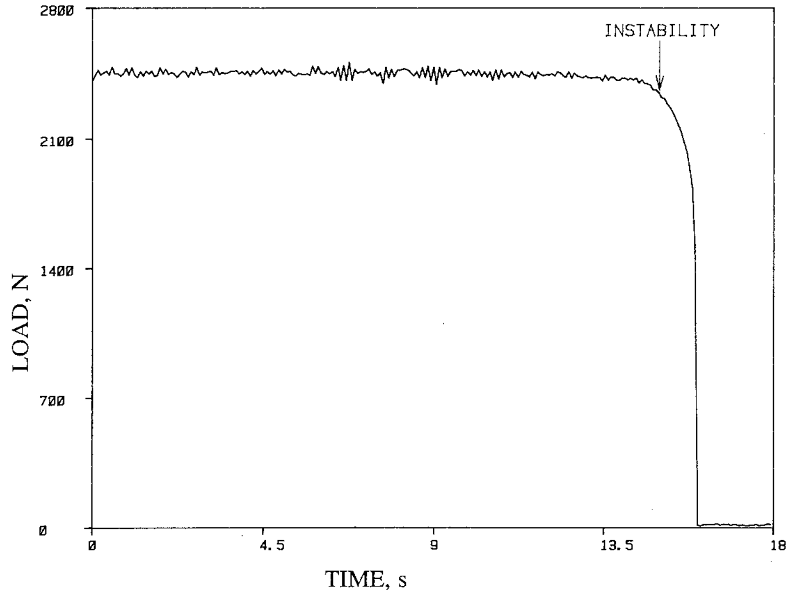

Fig. 4. Load history associated with the strain record shown in Fig. 3. Tensile instability is defined here as a 2% drop in load. The irregularities in the load record are caused by electronic interference in the load cell circuit.

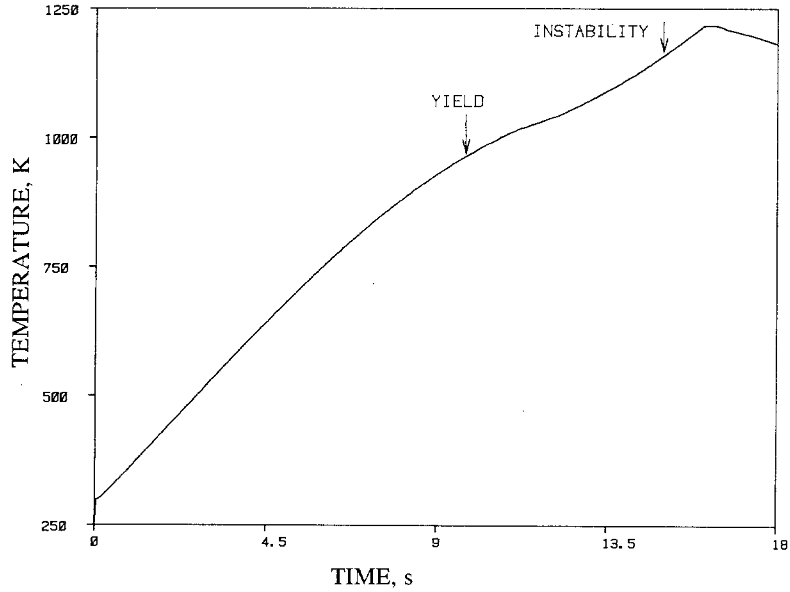

Fig. 5. Temperature history associated with the strain record shown in Fig. 3. The inflection between the yield temperature and the instability temperature is due to the endothermic ferrite-to-austenite phase change in steel.

In addition, the temperature history also shows the effects of an endothermic phase change (ferrite to austenite) in steel.

By analogy with the isothermal mechanical behavior of metals, where yield is defined as an arbitrary amount of plastic strain (usually 0.002), and the peak load is chosen as the failure criterion, similar terms may be defined to describe the behavior of rapidly heated metals. The yield temperature is that temperature at which 0.002 of plastic strain has occurred beyond thermoelastic efects. The failure or "instability" temperature is that temperature at which the load drops to a certain percentage of the original load and is used as a failure criterion.

What is of interest is the ability of metals to deform and work harden in response to the initial softening induced by the rapid heating so that the load remains stable up to large strains and high strain rates. It is this phenomenon that has not been studied much.

Depending on the alloy system and the initial stress established in the tensile test specimen, a variety of displacement or strain histories may be observed. Most metals, like the low-carbon steel shown in Fig. 3, soften on heating. There are, however, some alloy systems that do not. Two examples of alloys that undergo some strengthening reactions when heated are 304

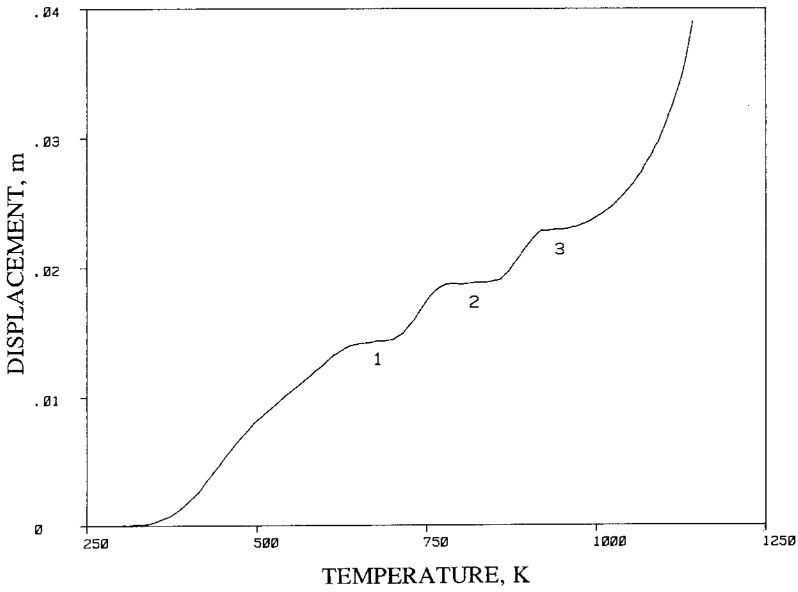

Fig. 6. Steps in a temperature vs displacement record for a 0.127-m length of 617 Inconel initial stressed to 446 MPa and heated up at a rate of approximately 90 K $\cdot$ s^{-1}. There are three distinct temperature ranges during which plastic deformation is halted.

stainless steel and 617 Inconel. When these materials are initially stressed to a point just above the isothermal yield at room temperature, the application of heat initiates plastic deformation at low temperatures. This deformation will accelerate but then suddenly stops when a critical temperature range is crossed. As shown in Fig. 6, the temperature vs displacement record for 617 Inconel exhibits three steps, indicating that different strengthening reactions come into play as the alloy is heated up. These materials also exhibit very large strains or displacements up to instability.

In many engineering applications the original cross-sectional area and the initial gauge length are used to calculate the stress–strain behavior of a metal. An example of this practice is found in the definition of the ultimate stress, where the load at tensile instability is divided by the original cross-sectional area. To characterize the mechanical behavior of rapidly heated metals, similar definitions are adopted. The initial engineering stress on the tensile test specimen is used rather than the true stress. The distinction between true stress and engineering stress becomes important only when the material is loaded well above its yield point.

By running a series of constant-load rapid heating tensile tests over a range of initial engineering stresses, and noting the temperature at which the load starts to drop in each case, a temperature vs strength characterization for a metal can be developed. An example of this is shown in Fig. 7 for 617 Inconel. The term "instability temperature" is chosen to distinguish this type of strength characterization from the normal isothermal elevated temperature ultimate strengths. Comparison of the constant-load rapid heating instability temperature with the standard elevated temperature ultimate strengths shows a considerable difference at the higher temperatures ranges as also illustrated in Fig. 7. This apparent difference between the isothermal and the rapid heating methods should not be surprising since the thermomechanical histories associated with the two strength characterization methods are not the same.

There are several reasons for this behavior. One is the rate at which the strengthening mechanism or microstructure changes in the metal with heating. Most of the mechanisms responsible for microstructural change are diffusion controlled, which requires time. Part of the observed differences between isothermal and rapid heating mechanical behavior is due to the effects of thermal history on microstructure. A microstructure tends to persist to temperatures well above that at which it would normally change under rapid heating conditions. This has an important effect with respect to the yield temperature.

After the metal has yielded, and assuming that no stengthening reactions occur as was the case with stainless steel and Inconel, the strain rate accelerates. This process is controlled again by microstructural

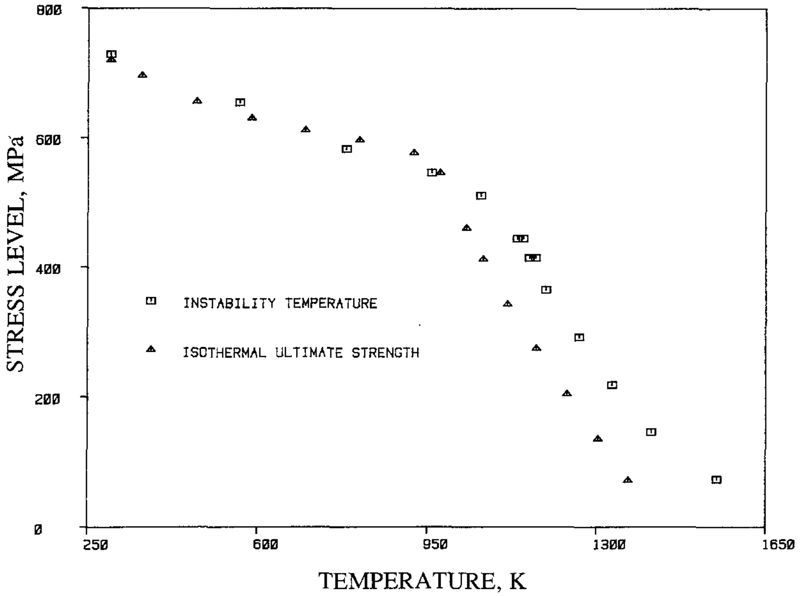

Fig. 7. Failure temperature vs initial stress level curve for 617 Inconel. At the lower temperatures (less than 950 K) there is little difference between a normal isothermal tensile test and a constant-load rapid heating tensile test. At the lower stress levels, under the conditions of constant load and rapid heating, the development of a tensile instability is delayed to higher temperatures. The isothermal ultimate strengths are from Ref. 4.

changes as the metal heats up, but another effect comes into play. The deformation mechanism of a metal is by the movement of line defects (dislocations) along crystallographic planes. At yielding it is primarily existing dislocations that start to move and allow the metal to plastically flow [6]. As the strain rate increases with increasing temperature, it is the density of dislocations and their interaction that become important.

A line defect in a metal has a finite velocity and requires time and energy to create [7]. This process introduces a deformation rate-controlling mechanism as the instability temperature is approached. In contrast to an isothermal constant-load test (creep test), there is no steady-state condition in a rapid heating environment. The metal reacts to oppose the changes caused by rapid heating and the resulting high strain rate (Le Chatelier's principle).

4. PHENOMENOLOGICAL DESCRIPTION OF DEFORMATION

As discussed earlier, the changes that occur in a stressed metal as it is heated rapidly are rather complex. The microstructure is often far from equilibrium for the temperature. The strain rate varies greatly as the material increases in temperature up to the instability temperature. The imposed mechanical boundary condition on the test specimen is a constant load which the servohydraulilc load frame will produce within the limits of its actuator response and velocity limits.

For many engineering problems it is sufficient to known some general or empirical description of the mechanical behavior of a material for an adequate or useful solution. This is the approach that is used here where the dominant mechanisms are known, but only qualitatively. Relating the observed behavior of a rapidly heated metal under load to some fundamental material properties is not, at this point, a feasible undertaking.

Up to the yield temperature there are only thermoelastic effects for which there are already well-developed structural analysis methods. The thermoelastic deformations up to the yield temperature may be described as

$$\varepsilon_{\mathrm{T}} = \varepsilon_{\text{Thermal Expansion}} + \varepsilon_{\text{Modulus Change}} \tag{1}$$

$$\varepsilon_{\mathrm{T}} = \alpha(T_2 - T_1) + \sigma\left(\frac{1}{E_2} - \frac{1}{E_1}\right) \tag{2}$$

where ε_{T} is the total thermoelastic strain, σ is the stress, α is the average coefficient of thermal expansion between T_1 and T_2, and E_1 and E_2 are the modulus of elasticity at temperatures T_1 and T_2, respectively.

Above the yield temperature, where large strains and high strain rates are encountered, there are no good descriptions of mechanical behavior. As is done often for isothermal creep, an Arrhenius rate equation is assumed to govern the plastic strain rate at any given temperature and state of stress with the form

$$\frac{d\varepsilon}{dt} = Ae^{-\Delta H(\sigma, \dot{T})/RT} \tag{3}$$

where A is the material characteristic strain rate parameter, $\Delta H(\sigma, \dot{T})$ is the activation energy related to thermomechanical history, R is the gas constant, and T is the thermodynamic temperature.

Here no assumptions have been made concerning the effect of stress on the strain rate as was done in Ref. 8. While it is known that the stress increases as the test specimen deforms, this effect is not addressed explicitly but simply lumped in with the rate equation. From the experimentally measured deformation behavior of a rapidly heated metal, the derivative is taken to obtain the plastic strain rate history. The logarithm of the strain rate is then plotted with respect to the inverse of the absolute temperature

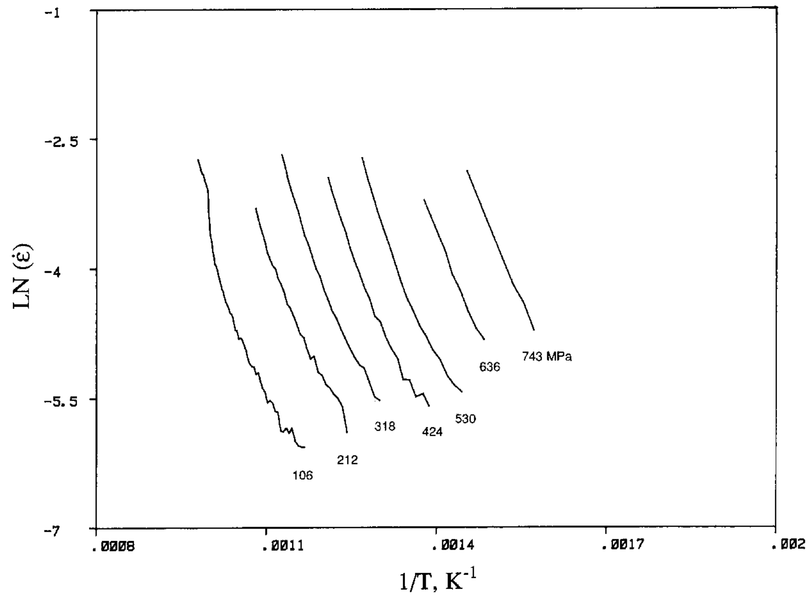

Fig. 8. Inverse absolute temperature vs log strain rate plot for a cold rolled low-carbon steel at several different stress levels. An approximately linear relationship is exhibited, indicating that the Arrhenius rate scheme is a reasonable assumption. The constants used in the rate equation are derived from this plot.

as shown in Fig. 8, which is a plot for a cold rolled low-carbon steel. It is seen that over a fairly large range of the plastic deformation for several stress levels an approximately linear relationship is exhibited, indicating that the Arrhenius rate scheme can be used as a good description of the plastic strain history after yield. The two constants in the rate equation will, of course, be specific for the thermomechanical history used in the experiments from which they are derived. Using the constants derived from the assumed rate equation and integrating for total plastic strain generates a sufficiently good match to experimental results for most engineering purposes.

5. TENSILE INSTABILITY IN RAPIDLY HEATED METALS

The flow stress of a metal is a function of the thermomechanical history to which it is subjected. The changes in microstructure and flow stress with temperature, the cross-sectional area reduction as the result of total plastic strain, and the work hardening produced by the deformation act together to maintain a constant load up to the instability temperature. This may be expressed as

$$\frac{dP}{dt}=\frac{d(\sigma A)}{dt}=A\frac{d\sigma}{dt}+\sigma\frac{dA}{dt}=0 \tag{4}$$

where P is the load sustained by the specimen, A is the cross-sectional area of the test specimen at time t, and σ is the stress at time t.

This condition applies up to the instability temperature. Since the flow stress of a metal is a function of the temperature, the total plastic strain, and the plastic strain rate, its rate of change with respect to time may be written as

$$\frac{d\sigma}{dt}=\frac{d\sigma(T,\varepsilon,\dot{\varepsilon})}{dt}=\frac{\partial\sigma}{\partial\varepsilon}\frac{d\varepsilon}{dt}+\frac{\partial\sigma}{\partial\dot{\varepsilon}}\frac{d^2\varepsilon}{dt^2}+\frac{\partial\sigma}{\partial T}\frac{dT}{dt} \tag{5}$$

where

$$\dot{\varepsilon}=\frac{d\varepsilon}{dt}$$

Here we have made some simplistic assumptions concerning thermomechanical history effects on the flow stress. From isothermal tensile tests it is known that the temperature, total strain, and strain rate affect the flow stess of a metal. One could imagine a series of three-dimensional surfaces relating the flow stress so strain and temperature at different strain rates. The problem is to relate these known effects to the rapid-temperature rise regime where the strain rate varies over a wide range. How the various changes in the metal interact to maintain a constant load can now be written as

$$\frac{dP}{dt}=\sigma\frac{dA}{dt}+A\left(\frac{\partial\sigma}{\partial T}\frac{\partial T}{dt}\right)+A\left[\frac{\partial\sigma}{\partial\varepsilon}\frac{\partial\varepsilon}{dt}+\frac{\partial\sigma}{\partial\dot{\varepsilon}}\frac{d^2\varepsilon}{dt^2}\right]=0 \tag{6}$$

where

$\sigma\dfrac{dA}{dt}$ ⇒ rate of change of load from reduction of cross-sectional area

$A\left(\dfrac{\partial\sigma}{\partial T}\dfrac{dT}{dt}\right)$ ⇒ rate of change of load from temperature effects on flow stress

$A\left[\dfrac{\partial\sigma}{\partial\varepsilon}\dfrac{\partial\varepsilon}{dt}+\dfrac{\partial\sigma}{\partial\dot{\varepsilon}}\dfrac{d^2\varepsilon}{dt^2}\right]$ ⇒ rate of increase of load from total plastic strain and strain rate effects

In a constant-load environment these three effects balance each other so that Eq. (6) applies up to the instability temperature. When the tensile instability occurs the load starts to drop and the failure criterion becomes

$$\frac{dP}{dt} < 0 \tag{7}$$

At this point the rate of increase in flow resistance from the work hardening produced from deformation is exceeded by the rate of annealing from the temperature rise and the rate of increase in stress level from the cross-sectional area decrease.

6. CONCLUSIONS

The observed deformation behavior of a stressed metal when subjected to rapid heating by the passage of an electric current is a complex phenomenon. The microstructural state of the metal is not known since it cannot be examined under the conditions of rapid heating. At best, only qualitative descriptions of the dominant mechanisms contributing to the deformation after yield and the development of a tensile instability are possible now.

It has been demonstrated that the load-carrying capacity of a rapidly heated metal is retained to higher temperatures than one would expect from isothermal tensile behavior. Also, it has been observed that in some alloy systems, such as 304 stainless steel and 617 Inconel, strengthening reactions occur which can halt plastic deformation when the metal is heated through certain temperture ranges.

It is possible, using some very simple empirical models such as an Arrenius rate equation, to develop useful descriptions of the deformations that occur after yield for those materials that do not exhibit hardening reactions. These descriptions can be used to predict the behavior of structural components when subjected to rapid volumetric heating.

The development of a tensile instability in a stressed metal heated by the passage of an electric current involves three competing mechanisms. It occurs when the increase in flow stress due to strain hardening can no longer keep up with the stress increase from the reduction in cross-sectional area and the degradation of the flow stress by the rising temperature. This is in contrast to the tensile instability that occurs in standard isothermal tensile tests, where only cross-sectional area decrease as the result of plastic deformation and strain hardening are the competing processes.

ACKNOWLEDGMENTS

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