JOURNAL OF APPLIED POLYMER SCIENCE VOL. VI, ISSUE NO. 21, PAGES 303-315 (1962)

Apparatus for Studying the Effects of Rapid Thermal Cycles and High Strain Rates on the Elevated Temperature Behavior of Materials

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INTRODUCTION

The demands of modern technology for structural materials for missiles, high speed aircraft, nuclear reactors, gas turbines and numerous other modern devices have rendered many conventional mechanical testing procedures obsolete. The determination of design criteria for structural alloys under service conditions involving high strain rates, high operating temperatures, and temperature variations approaching thermal shock is impossible with the best testing apparatus available only a few years ago.

To provide useful design data for effective utilization of materials under extreme conditions of temperature and loading, special testing apparatus is required. The following report describes a testing device designed to evaluate the influence of rapid thermal cycles and high strain rates on the mechanical behavior of structural metals and alloys.

Briefly, the testing device, somewhat facetiously called the "gleeble," consists of a high speed, time-temperature control device coupled with a high speed tensile testing apparatus. The gleeble permits conducting tensile tests with crosshead velocities as high as 4.5 in./sec. at any point in an automatically programed thermal cycle. The device is capable of consistently reproducing any thermal cycle provided the maximum rate of heating does not exceed 3000°F./sec. and the maximum cooling rate does not exceed approximately 350°F./sec. at 1000°F. (The limitation on cooling rates is also subject to the dimensions of the test specimen and the thermal characteristics of the material.) Shock heating at rates up to 15,000°F./sec. may also be studied using the apparatus; although thermal overshoot amounting to a few per cent of the programed maximum temperature must be expected. Metallic specimens ranging in size from $^1/_8$ in. diam. up to a cross-sectional area of 0.23 in.^{2} can be subjected to programed heating and cooling with effective gage lengths ranging from 0.2 to 6 in. and tested to destruction in tension.

In addition to tensile testing, the apparatus can be used to conduct investigations of the influence of rapid thermal cycles on the microstructure, transformational behavior, short-time creep behavior and short-time stress rupture strength.

DESCRIPTION OF THE TESTING APPARATUS

General

Figure 1 shows a general view of the gleeble. Visible at the right is the high speed tensile testing device, which utilizes two tandem mounted 9-in. air cylinders, located at the rear, to provide horizontally applied tensile loads up to 10,000 lb. The rate of crosshead motion is controlled within close limits by displacement of a captive volume of hydraulic oil from one end of a regulating cylinder to the other through a compensated hydraulic flow control valve. An electrical resistance, strain gage type of load cell in series with the movable crosshead provides an electrical signal proportional to the instantaneous load for recording purposes. Figure 2 shows the load cell, the movable crosshead with its precision ground cylindrical ways, and the general layout of the testing station. The axis of loading and the specimen axis are maintained in accurate alignment by four preloaded linear ball-bushings in which the cylindrical ways are supported. The distance between the fixed and the movable crosshead can be readily adjusted to any value from 0.5 to 8 in.

The base of the testing device contains a 50-kv-a transformer which supplies heating current to the specimen via the water-cooled copper alloy wedge-type grips contained in the fixed and movable platens. Also visible in Figure 2 is an automatic precussion welder (mounted on the fixed platen at the right) which is used to attach the thermo-

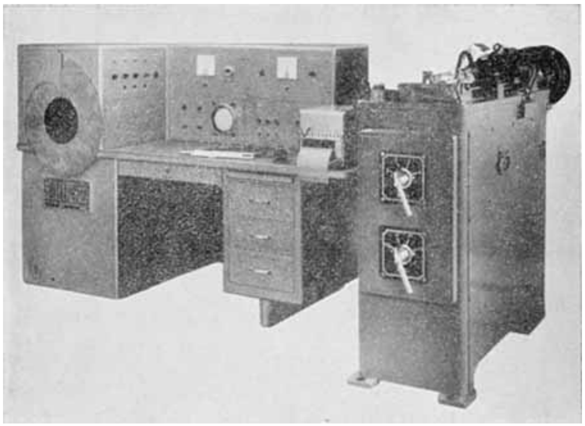


Fig. 1. General view of the gleeble.

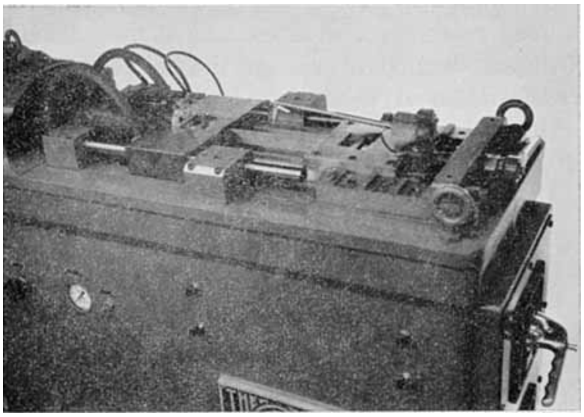


Fig. 2. Close-up of testing fixture.

couple used in controlling the specimen temperature.

An "infinite resolution" type of rectilinear potentiometer, mechanically connected between the fixed and the movable crosshead, provides an electrical signal proportional to the instantaneous position of the moving crosshead for recording of total strain during testing.

The control console is visible at the left in Figure 1. The equipment shown has a cam-controlled reference generator mounted in front at the left. This reference generator programs the entire testing procedure automatically and insures proper synchronization of the instant of application of the load and the operation of the recording apparatus with the desired point in the thermal cycle under study. The interchangeable sheet metal cam mounted at the front of the reference generator actuates the slider on a potentiometer to provide an output voltage which varies with time in accordance with the desired instantaneous variation in specimen temperature.

Controls for the reference generator and built-in calibrating circuitry for the oscillograph elements used in recording load and temperature are conveniently mounted on the side panel just to the right of the reference generator.

All operating controls, instrumentation power supplies, and a monitoring oscilloscope are located on the apron at the rear of the desk top. The direct-developing electromagnetic oscillograph used for recording of test data may be seen at the right end of the console desk.

The Control System

Figure 3 shows a block diagram of the control system which functions as follows.

1. A reference potential which varies with time in accordance with the desired time-temperature cycle is obtained from the reference generator A at the left.

2. This voltage is compared with the output of the 0.010-in. diam. control thermocouple, previously percussion-welded to the surface of the specimen (located below and to the right of the reference generator in Fig. 3).

3. A chopper B operated in synchronism with the supply line frequency samples the error-signal obtained by comparing the outputs of the reference generator and the control thermocouple. The sampling operation is conducted during a brief interval during each half-cycle of line frequency when heating current is purposely prevented from flowing in the specimen. (In this way, spurious voltages induced in the thermocouple leads by the heating current in the specimen are prevented from interfering with the control action.)

4. The circuitry contained in blocks C through K converts the error-signal pulse, admitted to the front end B by the chopper, to a voltage signal suitable for controlling the electronic contactor M.

5. When the specimen temperature is instantaneously below the correspondence point, the magnitude and polarity of the resulting error-signal results in firing the electronic contactor. This in turn permits current of the proper magnitude to pass through the primary of the heating transformer N. The control provides an automatic proportioning rate control action to bring the specimen temperature into correspondence rapidly without noticeable overshoot.

6. When the specimen temperature is instantaneously above correspondence, the control automatically prevents firing of the contactor until the specimen cools to the proper instantaneous temperature value.

7. The overall dynamic response of the control maintains the specimen temperature within less than 15°F. of the desired temperature at all times. Adjustable microswitches in the reference generator may be set to trigger the loading operation, start and stop the oscillograph, and initiate other events as desired, all in proper synchronism with the thermal cycle.

TYPICAL APPLICATIONS

Hot Ductility Testing

The first application of the gleeble for measurement of the effect of rapid thermal cycles was made in a study of the hot cracking of weldments in high temperature alloys.[1,2] Figure 4 summarizes the actual thermal cycles experienced at two points in the vicinity of an arc weld made in $1^{1}/_{2}$ in. stainless steel plate, using an arc energy input of 70,000 joules/in. with an initial plate temperature of 72°F. Sheet metal cams were constructed from the data shown in Figure 4 and used with the reference generator to program these thermal cycles in the specimens undergoing testing. The evaluation of the effect of the weld thermal cycles on the elevated-temperature properties of the high temperature materials was conducted in two ways: (*1*)

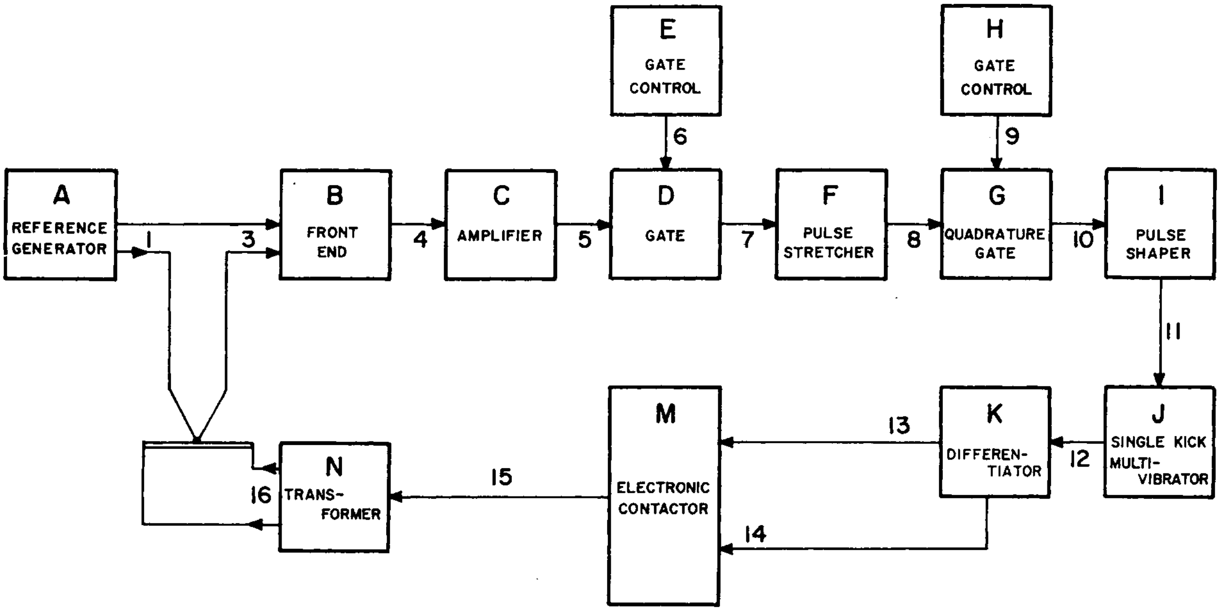


Fig. 3. Block diagram of electronic control mechanisms.

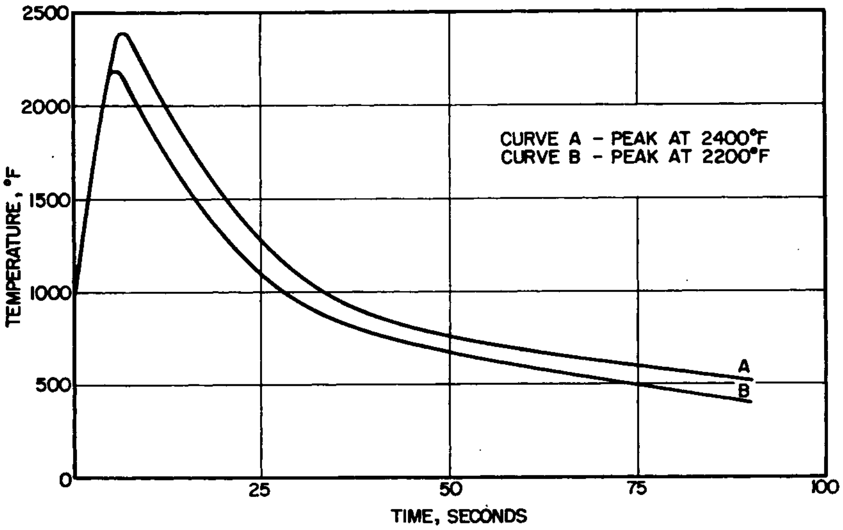


Fig. 4. Master thermal cycle for hot ductility experiments. Specimens broken at various temperatures in cycle.

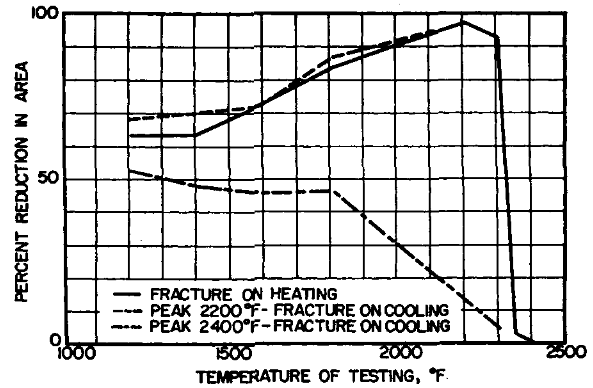


Fig. 5. Reduction in area as a function of temperature of testing type 347 wrought stainless steel.

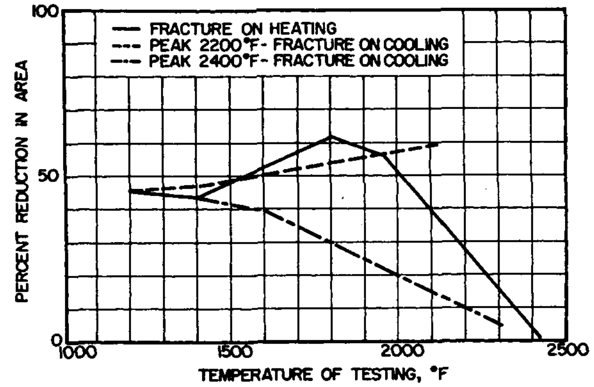


Fig. 6. Reduction in area as a function of temperature of testing type 316 Cb stainless steel—cast and heat treated.

evaluation of the effect of the heating portion of the thermal cycle alone; and (*2*) evaluation of the effect of following the thermal cycle to various peak temperatures, cooling along the thermal cycle to selected intermediate temperatures, and testing.

Typical test results for this type of testing, known as hot-ductility testing, are contained in Figures 5 and 6 for two different alloys. The data are reported as per cent reduction in area in tension as a function of testing temperature. The solid curve summarizes the variation in hot ductility of a heat of AISI type 347, as measured at the indicated temperatures during the heating portion of the thermal cycle *A* shown in Figure 4. It should be noted that the on-heating ductility increases from 64% reduction in area in tension at 1200°F. to a maximum of 97% at 2300°F. and then falls precipitously to zero at 2400°F.

The dashed curve in Figure 5 summarizes the hot ductility for the same alloy, when tested on the cooling portion of the thermal cycle *B* shown in Figure 4. All tests in this series were thus conducted after exposure for a brief interval to a peak temperature of 2200°F. Notice that the hot ductility is almost identical with the on-heating behavior shown by the solid curve.

The lower (dash-out) curve in Figure 5 shows the results of hot ductility tests conducted on the cooling portion of the thermal cycle with a peak temperature of 2400°F. (*A* in Fig. 4). Note that the brief exposure to a peak temperature of 2400°F. has caused metallurgical damage to the alloy, as indicated by the markedly lower hot ductility test data. For example, at 2300°F. on heating the measured ductility was 97%, whereas, when tested on cooling at 2300°F. after exposure to a thermal cycle with a peak temperature of 2400°F., the ductility was reduced to approximately 13%.

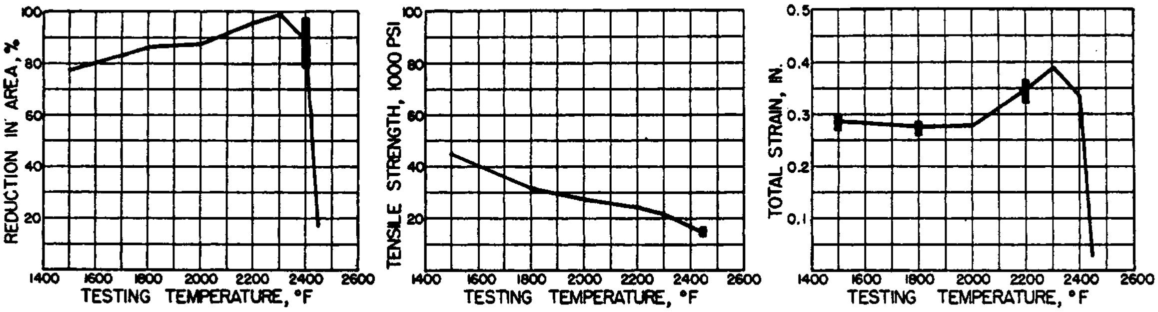
This severe reduction in elevated temperature ductility resulting from exposure to weld thermal cycles with peak temperatures near, but below, the melting point was found to correlate with the hot-cracking tendency of the particular alloy. Over the years, some several hundred heats of materials have been tested in this fashion. Some show severe impairment of on-cooling ductility, others show almost identical behavior when tested on cooling and on heating. In every instance where the hot-cracking tendency of weldments in a particular base metal is known, the materials with significant impairment in on-cooling ductility have proved more susceptible to hot cracking than have materials without this impairment.

Figure 6 illustrates a second type of hot ductility behavior. Notice that the on-heating ductility (solid curve) decreases gradually with increase in testing temperature above 1800°F. This type of behavior is associated with the presence of low melting impurity phases, segregated at the grain boundaries, and often results from poor melting practice. Such materials are usually prone to hot cracking during welding, and are therefore difficult to weld.

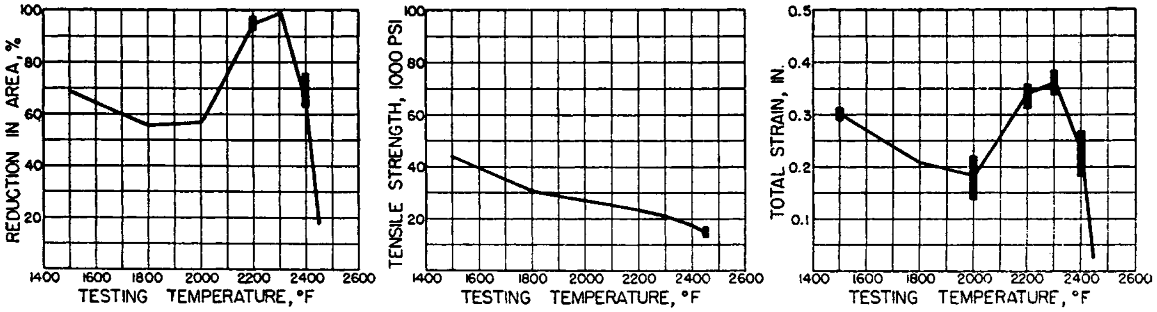
In subsequent research, the ultimate tensile strength of the base metal and the total strain at fracture were also measured and reported for similar testing procedures. Figure 7 shows typical test results for an experimental 16Cr-8Ni-2Mo alloy and a commercial heat of Hastelloy B when tested on heating and on cooling.

In all cases, the crosshead velocity was maintained constant at 2.5 in./sec. and the complete test required less than 0.02 sec. from the time of application of load to failure. This explains the significantly higher values of ultimate tensile strength than are reported as a result of conven-

Tested on heating

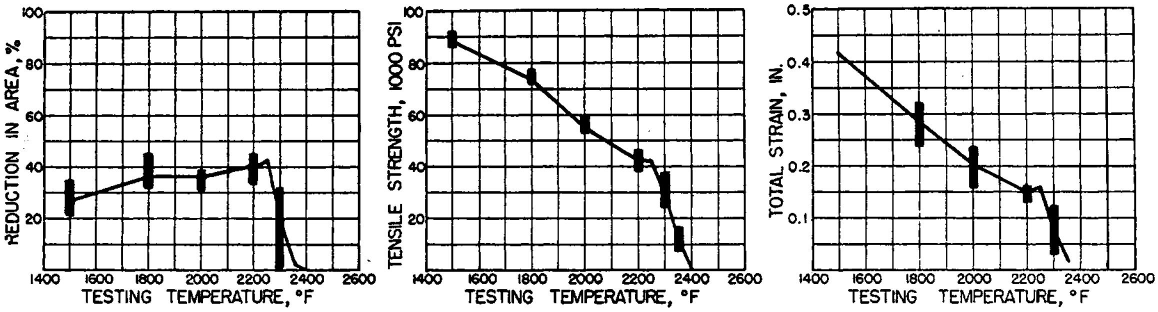


Tested on cooling from 2450° F

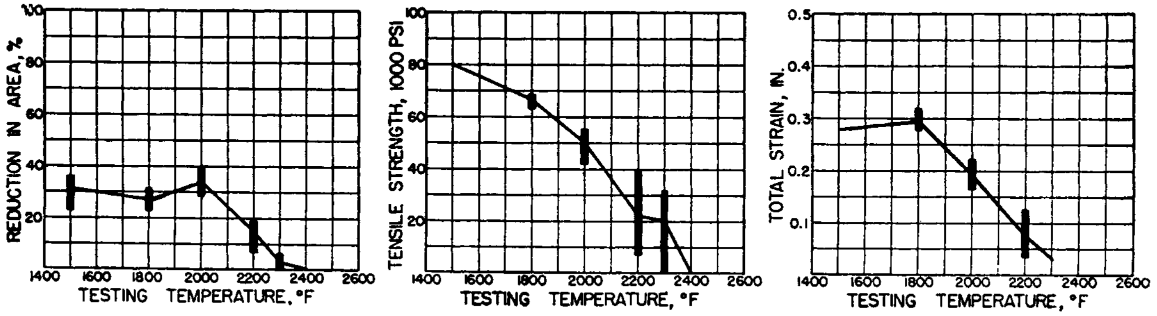


Hot-ductility test results—16-8-2, wrought, crucible, Code BE

Tested on heating



Tested on cooling from 2400° F



Hot-ductility test results—Hastelloy B, wrought, Heat B 1337, Code W

Fig. 7. Typical test results for experimental 16Cr-8Ni-2Mo alloy and a commercial heat of Hastelloy B when tested on heating and on cooling.

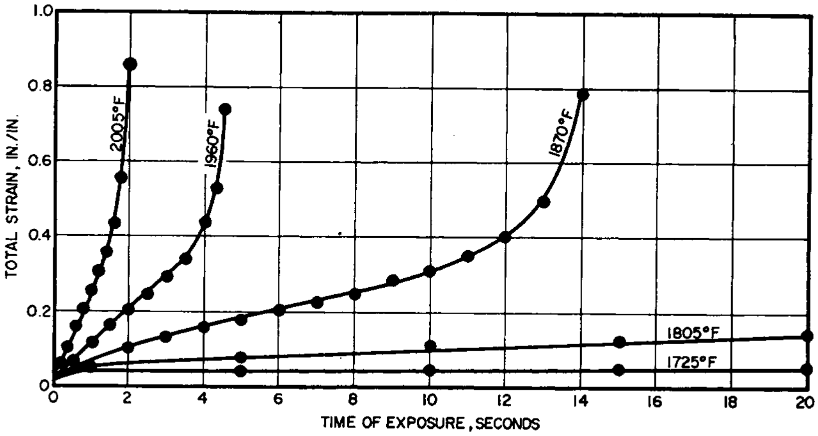


Fig. 8. Typical short time creep data, type 347 stainless steel for stress of 12,750 psi.

tional tensile testing procedure, which may require up to 20 min. at temperature. These data indicate that in applications where parts have a short life expectancy and creep is not a problem, higher design stresses should be possible.

Short Time Creep Testing

In applications where the life expectancy of a part at elevated temperature is short, but creep is important, the data shown in Figure 8 are applicable. In this instance, the test specimen was loaded with a constant load producing an initial axial stress of 12750 psi and heated to the indicated testing temperature at 1000°F./sec. The temperature and load were then held constant and the total strain on the specimen was recorded as a function of time. Although not shown in Figure 8, the shape of the curves for 1805 and 1725°F. was

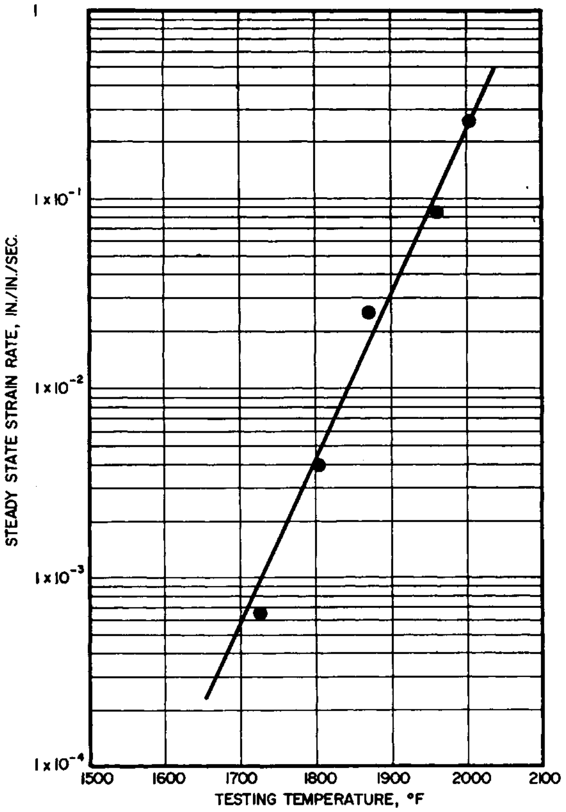


Fig. 9. Short time creep behavior, type 347 stainless steel, axial stress = 12,750 psi.

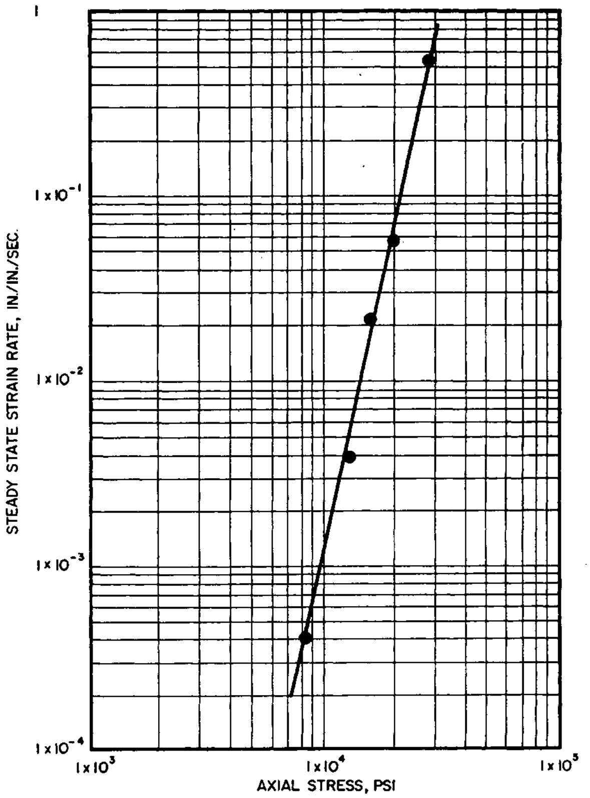


Fig. 10. Short time creep behavior, type 347 stainless steel, temperature —1805°F.

similar to that of the other three curves. The times to rupture ranged from about 100 to 1000 sec., respectively, although continuous records were not taken during these two tests.

It should be noted that a steady state creep rate is observed at each temperature (the linear portion of the creep curves). Figure 9 summarizes the influence of testing temperature on the steady state creep rate for the conditions shown in Figure 8. Note that the rate increases by a factor of nearly 500 over a temperature range extending from 1724 to 2005°F., a span of only 280°F. Note also that at 2005°F., the specimen strained at a rate of 0.26 in./in./sec. and failed after only 2 sec. at temperature.

Figure 10 illustrates the influence of the load, plotted as initial axial stress, on the steady state creep rate at 1805°F. Note that increasing the initial stress from 8200 to 27,500 psi caused the strain rate to increase by a factor of 1300.

It is believed that the ability to generate data of the type summarized in these figures would be difficult, if not impossible, to obtain by any other means. Nor is the data shown representative of the maximum capabilities of the apparatus, since controlled heating rates in excess of 3000°F. are possible, and the instant of application of the load can be programed as desired. In addition, the effect of the application of rapid thermal cycles under conditions of constant load remains to be explored.

Thermal Fatigue

Figure 11 shows a special thermal fatigue fixture designed for use as an accessory with the time-temperature control. A cylindrical specimen is clamped between two massive copper jaws, separated to provide a gage length of 2 in. The specimen is restrained from changing dimension axially by two massive aluminum webs which are firmly bolted to the sides of the copper jaws. Strain gages mounted on the aluminum webs permit continuous recording of the reaction forces produced in the webs by the expansion and contraction of the specimen.

The specimen is subjected to repetitive heating and cooling cycles using the high speed time-temperature control. Massive copper conductors connected between the copper blocks and the platens of the testing machine conduct heating current to the specimen.

Figure 12 shows a typical thermal cycle used in

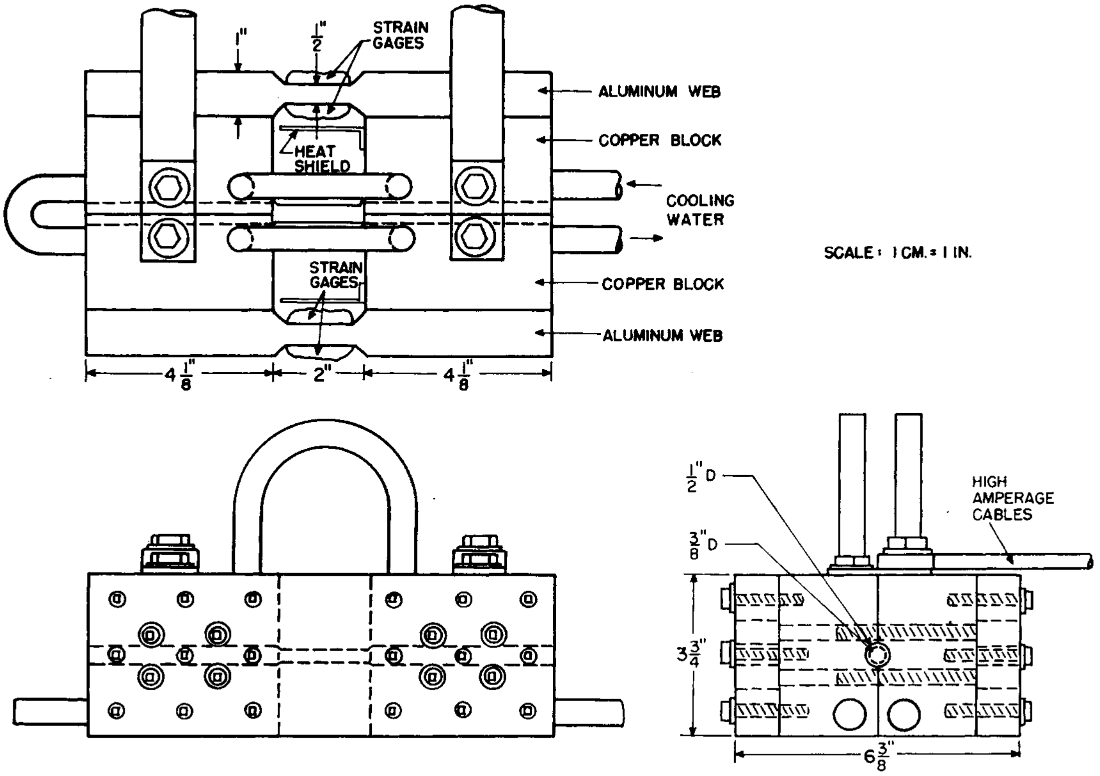


Fig. 11. Thermal fatigue clamping jig and specimen.

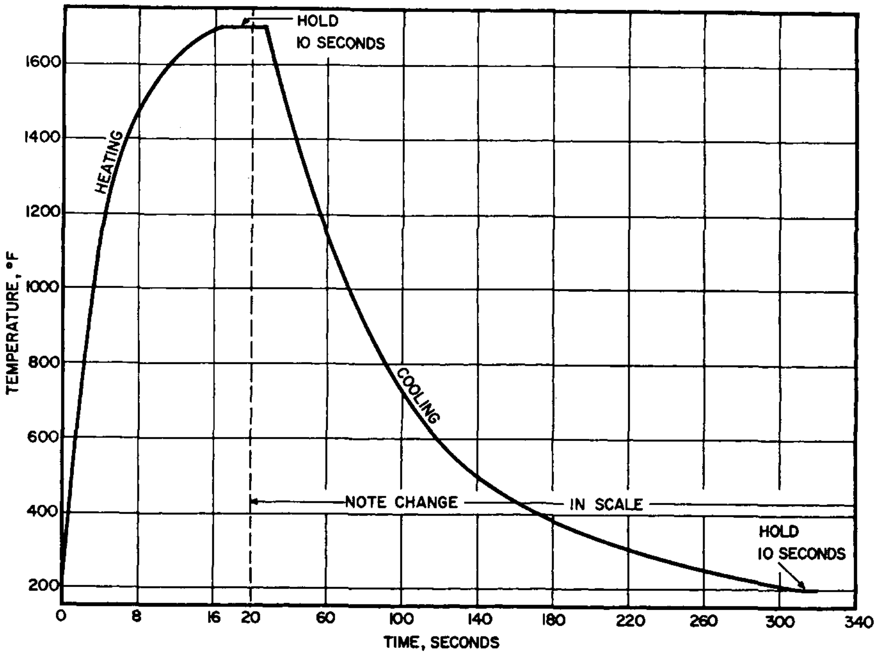


Fig. 12. Generalized exponential thermal cycle.

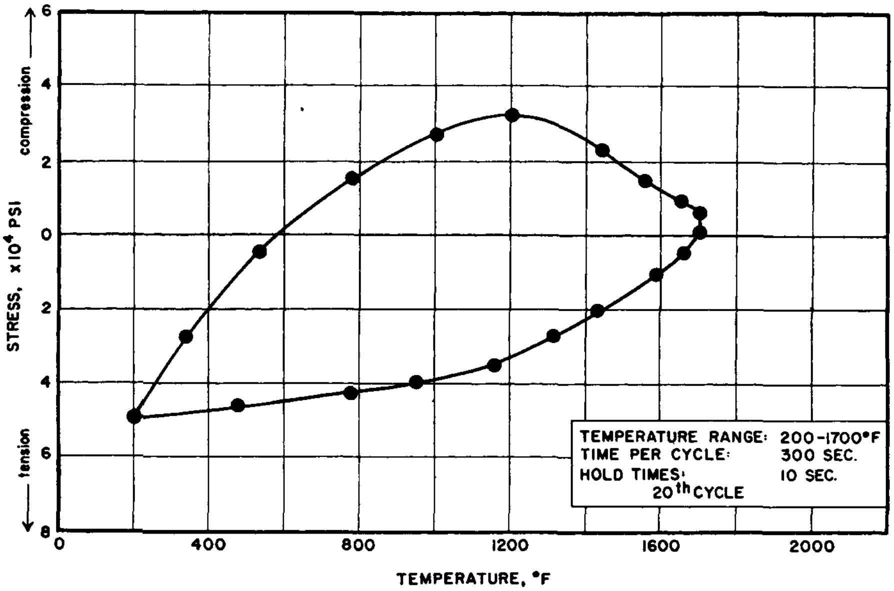


Fig. 13. Typical stress temperature loop.

conducting a thermal fatigue test. Note that the temperature of the specimen is made to rise to a peak of 1700°F. in 16 sec., held for 10 sec. at 1700°F., and then reduced exponentially to 200°F. in 280 sec. Figure 13 shows the variation in stress induced in the specimen as a function of temperature during the 20th repetition of the thermal cycle. The stress-temperature cycle proceeds in a clockwise direction around the loop, changing from tension at 200°F. to a maximum compressive stress of 33,000 psi at 1200, falling to 6,000 psi compression at 1700°F., then returning to 50,000 psi in tension at 200°F. on cooling.

Figure 14 shows typical results of such tests conducted for several different cyclic variations in temperature. The number of cycles to failure N_f is plotted as a function of maximum temperature for several different minimum temperatures. It is

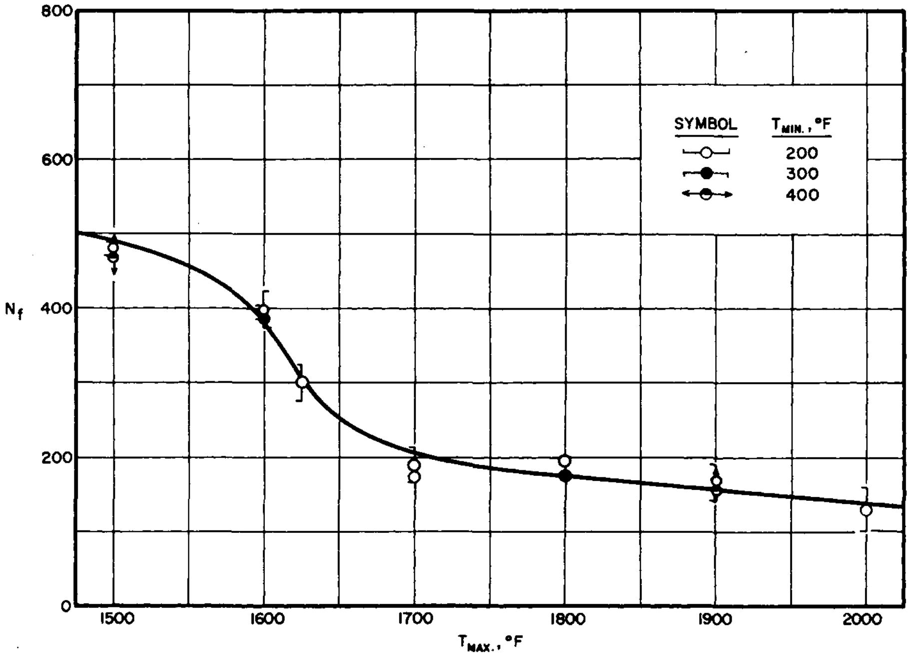


Fig. 14. Number of cycles to failure as a function of maximum temperature.

interesting to note that the life appears to be dependent only on the peak temperature and not on the temperature difference experienced by the specimen during each thermal cycle, the region of rapid decrease in N_f was found to coincide with the recrystallization temperature of the alloy.

Effect of Rapid Thermal Cycles on Transformation Behavior

Figure 15 shows a high speed dilatometer for use with the gleeble in conducting studies of the effect of rapid thermal cycles on allotropic transformation behavior. The dilatometer visible at the right consists of an H frame with an "elastic" hinge located at the midpoint of the vertical arms. Quartz or alumina feeler rods, located at the bottom of the H frame, bear on the transverse dimension of a specimen held in the jaws of the gleeble. Any change in the transverse diameter of the specimen causes a corresponding motion of the feeler rods which, in turn, move the slider on an infinite resolution type of rectilinear potentiometer shown at the top. This motion provides a variation in output voltage suitable for recording and permits obtaining a continuous record of changes in specimen dimension during heating. By plotting the transverse dilation of the specimen as a function of the specimen temperature, any transformation involving a

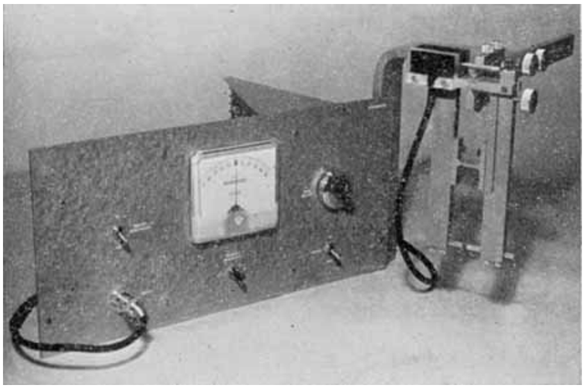


Fig. 15. General view of dilatometer attachment.

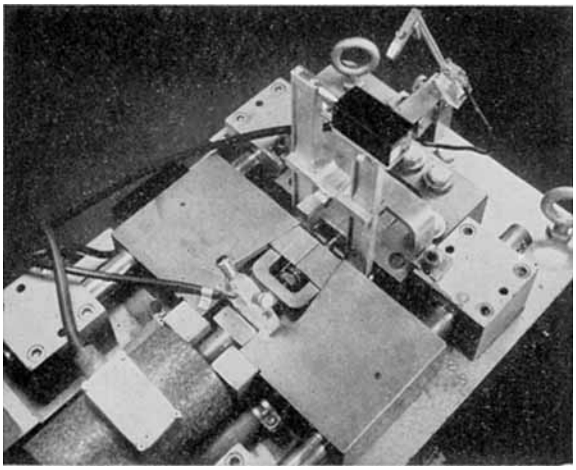


Fig. 16. View of dilatometer in use.

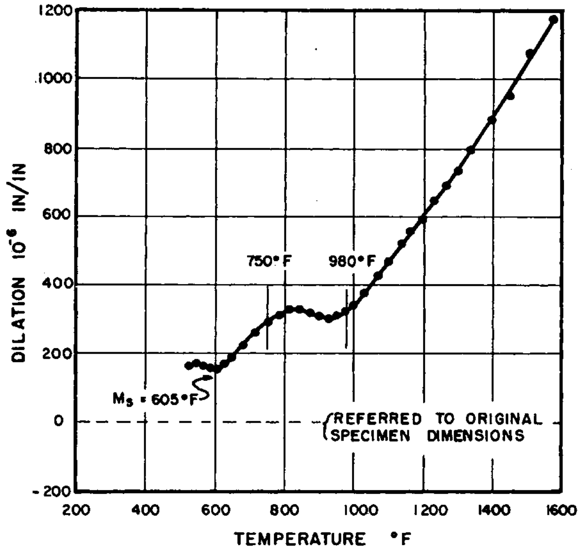


Fig. 17. Typical dilatometric data for steel AR austenitized at 1600°F. and cooled at a rate of 35°F./sec. at 1300°F.

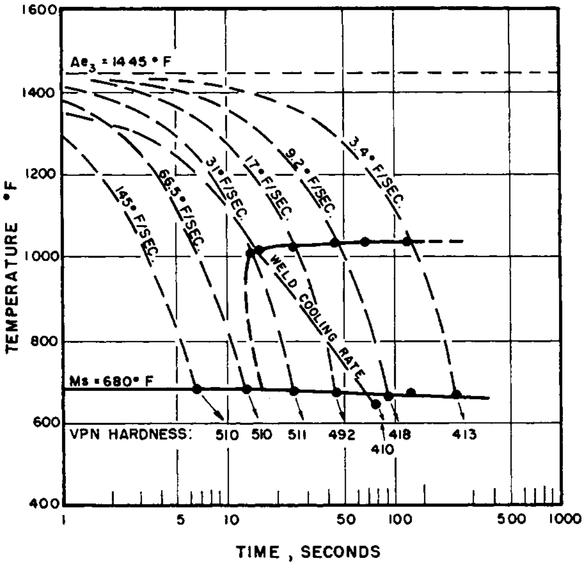


Fig. 18. Continuous cooling diagram steel LR austenitized at 1600°F.

volume change may be detected. A voltage-regulated power supply and adjustable bridge circuit for use with the dilatometer are shown at the left in Figure 15.

Figure 16 shows an experimental model of the dilatometer in position in the test throat of an early gleeble. Figure 17 shows a typical plot of dilation as a function of temperature obtained by cooling a commercial steel from 1600°F. at an exponential rate. The hump in the curve at 800°F. is caused by the transformation of austenite to bainite, while the smaller hump near 600°F. reflects the transformation of the remaining austenite to martensite.

Figure 18 shows a compilation of transformation data in the form of a continuous cooling transformation diagram. This plot shows the influence of cooling rates ranging from 145 to 3.4°F./sec. on the transformation behavior of a typical alloy steel. The data shown were subsequently utilized in establishing optimum welding conditions for this particular steel.[3,4]

Reproduction of Weld-Heat-Affected Zone Microstructures

In addition to the above applications, the Gleeble is in almost constant use reproducing the individual microstructural changes caused in the heat-affected zones of arc welds. By exactly duplicating measured weld thermal cycles in properly designed specimens, a volume of a particular microstructure can be produced of suitable size for subsequent examination and testing. Figure 19 shows a typical specimen geometry used to measure the influence of weld thermal cycles on notch toughness.

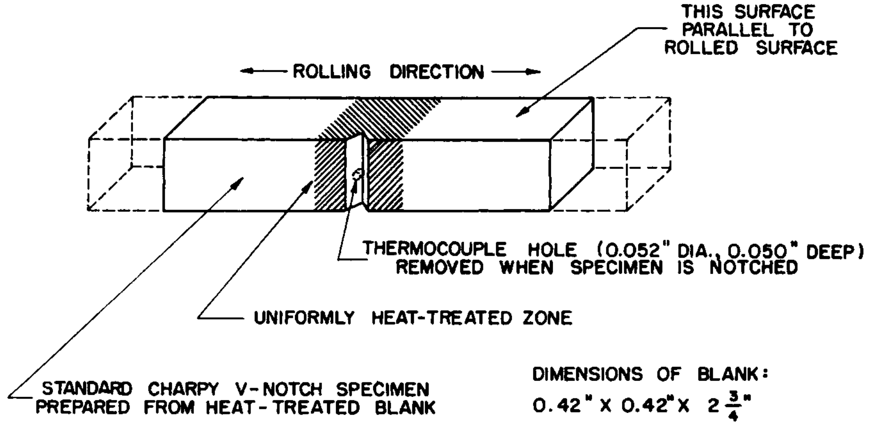


Fig. 19. Details of specimen preparation.

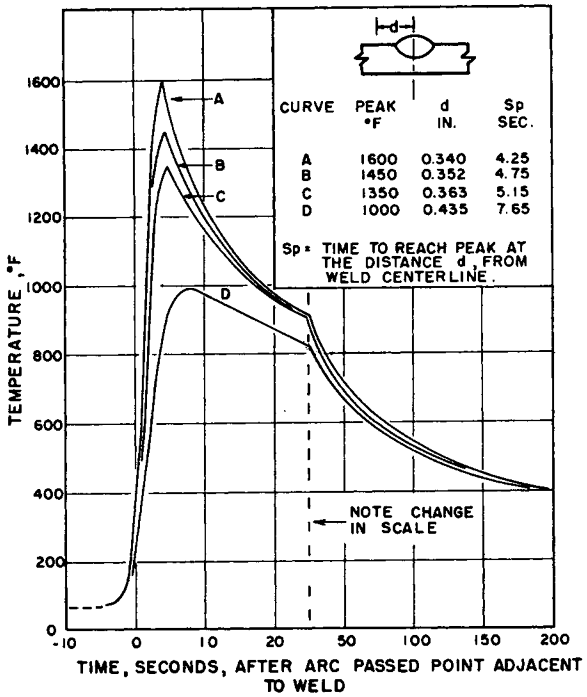


Fig. 20. Thermal cycles adjacent to arc welds in $^1/_2$ in. steel plate. Energy input 47,000 joules/in. No preheat.

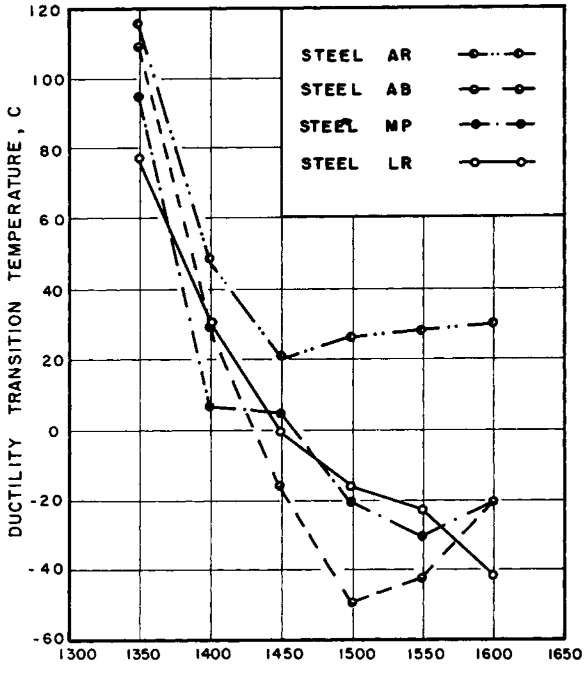


Fig. 22. Summary of ductility transition temperature as a function of peak temperature of the weld thermal cycle.

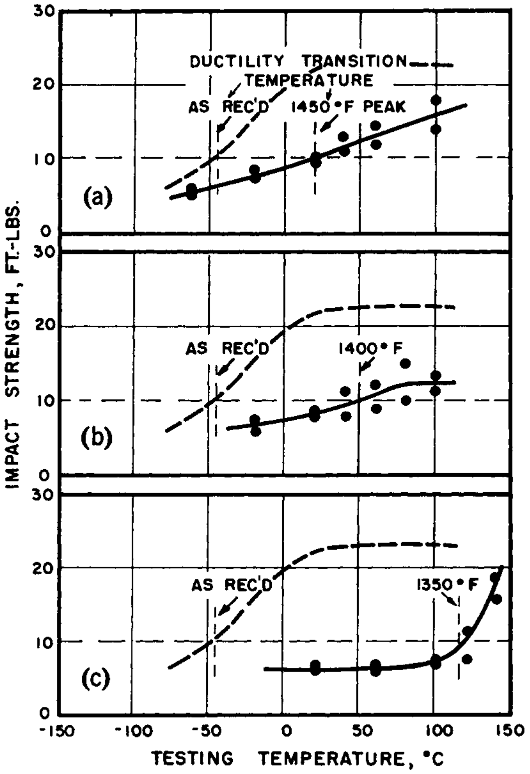


Fig. 21. Steel AR exposed to weld thermal cycles with indicated peak temperatures: (*a*) 1450°F. peak, (*b*) 1400°F. peak, and (*c*) 1350°F. peak.

A region $^1/_4$ in. long is produced in the center of each specimen having the exact microstructure found at the particular point in the weld-heat-affected zone experiencing the same thermal cycle. By notching and impact testing several such specimens over a range of testing temperatures, the impact strength transition temperature of the particular microstructure may be determined. Figure 20 shows some typical measured weld thermal cycles investigated by this means, and indicates the location of the points experiencing each thermal cycle. Figure 21 shows the impact strength as a function of testing temperature for three different microstructures reproduced by this means. Note the difference in impact transition behavior shown for these structures. Figure 22 shows a summary compilation of the effect of the peak temperature of the thermal cycle on the ductility transition temperature for four different steels.

Data of this type have been of great assistance in weldability studies and in determination of optimum welding procedures for difficultly weldable steels.

SUMMARY

Although the treatment of the subject has been brief, it is hoped that this report has served to summarize the operational details and a few of the more interesting applications of this novel testing device. Annotated references have been made to published works describing the applications in more detail.

Work is now in progress on an extensometer with sufficiently high frequency response to permit plotting of complete stress strain curves at strain rates up to 25 in./in./sec. Although it was hoped that a description of this device and its application could be included in this report, technical difficulties and lack of time forbid.

The author wishes to thank his associates at Rensselaer Polytechnic Institute for their cooperation, in particular the many graduate students in the Department of Materials Engineering, past and present, responsible for generating much of the data shown.

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Synopsis

A new research tool is described which permits determination of short-time elevated temperature properties of metals and alloys. Test specimens are heated by their own resistance to the flow of a large magnitude heating current, and a rapid-acting electronic-proportioning rate-control action permits achieving programmed heating of the specimen under test at rates up to and exceeding 3000°F./sec. with negligible thermal overshoot. Complete thermal cycles involving complex programs of alternate heating and cooling may be automatically programmed by means of a special electronic reference generator with a dynamic accuracy of ±15°F. for peak temperatures up to the working limit of existing thermocouple materials. The electronic programming device also initiates testing of the specimen in tension with any desired rate of crosshead motion up to 4.5 in./sec. with loads up to 10,000 lbs. Specimen temperature, load, and crosshead position as a function of time are automatically recorded by a direct-developing recording oscillograph. Examples of recent applications of the apparatus to some metallurgical problems are described briefly, and suggested areas of future application are summarized.

Résumé

Un nouvel instrument de recherche est décrit permettant de déterminer les propriétés des métaux et alliages durant une courte durée à température élevée. Les échantillons d'essais sont chauffés par leur propre résistance au passage d'un courant de chauffage important; un contrôle rapide et règlant électroniquement la vitesse permet de réaliser un chauffage programmé de l'échantillon à des vitesses jusqu'à et au delà de 3000 F°/sec sans perte thermique sensible. Des cycles thermiques complets comportant des programmes complexes de chauffage et refroidissement alternatifs peuvent être réalisés automatiquement grâce à un générateur spécial électronique de référence avec une précision dynamique de ±15°F pour les pics de températures jusqu'à la limite de travail des thermocouples existants. Le système programmateur électronique permet également l'examen de l'échantillon sous tension utilisant n'importe quelle vitesse de mouvement jusque 4.5 pouces/sec. avec des poids allant jusqu'à 10.000 livres. La températures de l'échantillon, la charge et les positions sont automatiquement enrégistrées en fonction du temps au moyen d'un oscillographe enrégistrateur direct. Des exemples d'application récents de l'appareil à certains problèmes métallurgiques sont brièvement décrits et les domaines d'application future sont résumés.

Zusammenfassung

Ein neues Forschungsgerät zur Bestimmung der Eigenschaften von Metallen und Legierungen bei kurzzeitiger Beanspruchung bei erhöhter Temperatur wird beschrieben. Testproben werden durch einen Heizstrom grosser Stärke infolge ihres eigenen Widerstandes erhitzt und eine rasch wirkende elektronische Kontrollvorrichtung erlaubt die Einstellung einer programmierten Heizung der Testprobe bei Geschwindigkeiten bis zu 3000°F/sec und darüber ohne wesentliche thermische Überschreitungen. Vollständige thermische Cyklen mit einem komplexen Programm abwechselnder Heizung und Kühlung können mit einem speziellen elektronischen Referenzgenerator mit einer dynamischen Genauigkeit von ±15°F für Spitzentemperaturen bis zur Brauchbarkeitsgrenze der bekannten Materialien für Thermoelemente automatisch programmiert werden. Die elektronische Programmierungseinrichtung löst auch die Spannungstestung der Probe mit jeder gewünschten Geschwindigkeit einer Kreuzkopfbewegung bis zu 4,5 in./sec und Belastung bis zu 10.000 Pfund aus. Probentemperatur, Belastung und Kreuzkopfstellung werden mit einem Oszillographenschreiber vom "Direct-developing"-Typ als Funktion der Zeit automatisch aufgezeichnet. Beispiele für neuere Anwendungen des Apparats auf einige metallurgische Probleme werden kurz beschrieben und ein Überblick über Vorschläge für eine zukünftige Anwendung wird gegeben.

Discussion

Question: Isn't this a quick method of determining time-temperature transformation?

Answer (Dr. Savage): Yes, it is. The summary curve (Fig. 18) is actually a form of time-temperature transformation curve. By the usual techniques, obtaining one of these curves will take from a week to a month, depending on how accurately you wish to obtain it. We can obtain a continuous cooling transformation curve in a day or two with our apparatus. We can also study cooling rates that just span the range of welding cooling rates very nicely; the device is ideally suited to studying the effects of welding on the transformation of the base metal. One of our men is working on the effect of rapid heating on the transformation of the structure which is stable at room temperature to austenite. This is of fundamental importance to the metallurgist. It is very difficult to obtain data with the use of more than a certain rate of heating, because by conventional means it takes it a while to get up to temperature. On the other hand, we can really force temperature changes at rates as high as 35°F./sec., and we find some rather interesting results from these studies.

Question: You have said that you got cooling rates as high as 500°/sec. How did you achieve that?

Answer (Dr. Savage): The specimen is cooled by a longitudinal flow of heat to the water-cooled copper jaws; if you wish to increase the cooling rate you must shorten the specimen and be satisfied with a narrower region of uniformity.

I may add that the temperature distribution in one of these specimens approximates a half lobe of a sinusoid. As you know, a sinusoidal is reasonably flat on the top.

One additional feature is inherent in the method. Specifically, the temperature distribution tends to become more uniform with more rapid heating. An 8-in.-long specimen exhibits a length of 6 in. of uniform temperature within 15°. This is well within 1% for peak temperatures above 1500°.

Question: What kind of thermocouple do you use?

Answer (Dr. Savage): We use all kinds, but usually either chromel–alumel or platinum–platinum rhodium. We make our own thermocouples by cross-wire welding. We find that this is the only way that we can get a hot junction small enough to follow the temperature. The two wires are crossed and resistance-welded to form a hot junction. Then they are trimmed through the middle of the cross-wire weld so that the hot junction has a thickness of roughly five thousandths of an inch. The hot junction is percussion-welded to the surface, by means of a bank of capacitors charged to high voltage, and this in turn destroys all but about a thousandth of an inch of this hot junction. We are conducting some experiments with extremely rapid cooling. After being heated at several thousand degrees Fahrenheit per second, the specimens are subjected to a spray quench; we have measured cooling rates at the specimen surface of nearly 200,000°F./sec.

Question: Have you a thermocouple on the specimen surface?

Answer (Dr. Savage): Yes. Many people think the response time of a thermocouple is slow and you will find a great many misconceptions in the literature, I believe. The response time of the thermocouple is limited primarily by the rate at which one can change the temperature of the hot junction. It is a solid-state device, effectively, and the output of the thermocouple, as far as I can determine from any of our measurements, is more rapid than any temperature change we have ever been able to make. However, if you get a large hot junction on the thermocouple, the response time of the thermocouple is limited by the rate at which heat can be supplied to the junction. Or if you attach the thermocouple with an air film in between, so that heat must be transferred across an interface, the speed of response is decreased. We avoid these problems with our technique.

Question: How do you physically record the temperatures?

Answer (Dr. Savage): We use the control thermocouple and run the output into an electromagnetic oscillograph which has sensitivity adequate to give us practically full-scale deflection from the output of a chromel–alumel thermocouple. The amount of current drawn from the thermocouple is only of the order of a few microamperes. Consequently, we do not introduce any significant errors due to using this both as a control and as a measuring thermocouple. The frequency response of the galvanometer is the major limiting factor. When we need higher frequency response than we can obtain with the galvanometers without amplification, we utilize special transistorized amplifiers as impedance matching devices that allow us to use galvanometers of higher frequency response.