A New Technique for Heating Specimens in Split-Hopkinson-Bar Experiments Using Induction-Coil Heaters

by Z. Rosenberg, D. Dawicke, E. Strader and S.J. Bless

ABSTRACT—A new technique to heat metallic specimens, in split-Hopkinson-bar experiments, is presented. The heating is achieved with induction coils surrounding the specimen. The main advantages of this technique are (1) a relatively fast heating rate, (2) localization of the heated volume, and (3) heating achieved without touching the specimen. Experimental results for several metals, in terms of high strain-rate stress-strain curves at elevated temperatures, are presented and discussed.

Introduction

The split Hopkinson bar (SHB) is widely used for determining dynamic response of solids under high rates of strain (10^2–10^4 s^{-1}). The basic principles of the SHB are described in Refs. 1 and 2. The University of Dayton Research Institute employs a SHB which was modified by Nicholas[3] to measure high strain-rate tensile tests. Bless *et al.*[4] give a detailed description of this system.

During the past 20 years many workers designed various heating systems in order to perform high-temperature tests in the SHB system (see Ref. 5). Heating of the specimen was achieved by placing various kinds of heaters near it. There are two major difficulties with this technique: (1) the time needed to heat the specimen is relatively long; and (2) the heating is not localized and a large volume (including bar tips) is heated. Thus, a temperature gradient is established along the loading bars to either side of the specimen. Such gradients produce variations in the elastic modulus of the bars and hence variations in the elastic velocity. As a result, elastic pulses propagating along the bar suffer from partial reflections and from change of amplitude. Several techniques to reduce these temperature gradients and how to account for them in the data-reduction process are described in Ref. 5. The need to heat the specimen at high rates also emerges when one wants to avoid microstructural changes (like grain growth and recrystallization) which can occur at elevated temperatures. This was the case for aluminum alloys in Ref. 6, which we shall later discuss.

The purpose of the present paper is to describe a rather simple heating technique which is both fast and localized thus overcoming the difficulties described above. The heating is achieved with induction coils which surround the specimen and heat its central region. Temperatures of near 700 °C, in steel specimens, can be reached in less than a minute. We shall first describe the general features of induction heating and their application to SHB experiments. This is followed by experimental results for some metals at high strain rates (around 10^3 s^{-1}) which were tested at temperatures up to 700 °C.

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Induction Heating

The specimen to be heated is surrounded by an induction coil which carries a high-frequency current as shown in Fig. 1. The material to be heated is not part of a closed electrical circuit so the generation of heat is solely by induction. The heating of metallic parts is the result of internal energy losses. In ferrous materials, having magnetic properties, these losses are through both eddy currents and hysteresis (up to the Curie point). For higher temperatures and for nonmagnetic metals, the only losses present are due to eddy currents. Heating rates will be lower for nonmagnetic metals and for ferrous metals above their Curie points.

The specimens in our experiments were heated by a radio frequency generator manufactured by Lindberg/cycle Dyne (Model No. A-50). This generator uses the 240-V line power, which is stepped up via a transformer to about 5000 Vac. This high voltage is rectified and the resulting dc is supplied to an RF power oscillator operating at approximately 450 kHz. The output of this oscillator is about 5 kW and this is coupled to the sample by using 0.25-in. copper-tubing coils, which surround the sample. The output power is usually set to maximum in order to make the heating process as short as possible.

Since the magnetic field varies inversely with the square of the distance between the specimen and the coil, one wishes to work with the smallest possible coils if the heating time is a limiting factor. Our coils were larger than the Hopkinson-bar diameter (12.7 mm) by only about 3 mm.

Experimental Procedures

The Nicholas version of a tensile Hopkinson bar, which we use, utilizes a threaded specimen which has a shape similar to the standard tensile specimen. The specimen is threaded on both sides into the bar and a collar is placed as shown in Fig. 2. The impact of the striker bar generates a compression pulse in the first pressure bar whose amplitude depends on the striker velocity and whose length is twice the longitudinal elastic-wave transit time in the striker bar. This compression pulse travels down the pressure bar and through the composite cross section of collar and specimen in an essentially undispersed manner (as if the specimen were not present). This is so because of the collar which carries the compressive load. When the pulse reaches the free end of bar 2, it reflects back and propagates as a tensile pulse. When this pulse reaches the collar and specimen region it 'disconnects' the collar from the bars, since it is not fastened to them, and the entire tensile load is transferred to the specimen. In order to avoid heating the collar, we replaced the metallic collar by a ceramic one. Alumina AD-995 (manufactured by Coors) was used because it has an acoustic impedance which is very close to that of steel. This matching of impedance results in a smooth passage of the stress wave from the first bar to the second through the ceramic collar.

The temperature of the specimen just prior to loading was measured by use of a thermocouple inserted through a hole drilled in the ceramic collar. The thermocouple touched the specimen so that the temperature was monitored continuously during the heating process. When the temperature reached the desired value, the striker bar was fired. In order not to heat the bars themselves too much, we heated the specimens for about one to two minutes in all the experiments described here. We found that with the double-wound arrangement, we could heat steel specimens to 700°C in about one minute. We also tried a single-coil configuration, but this was not as efficient as the double-coil probably because of worse matching between specimen and field. In some of the experiments, the ends of the bars were heated but their temperature was much less than that of the specimens and the heated portion of the bar extended to only about 10 mm. In order to determine the effect of such heating on the wave-propagation characteristics, we conducted two experiments in which the tips of the bars touched each other and were heated to 200°C and 400°C. The transmitted and reflected pulses were compared with those obtained at room temperature and the difference in the measured strain pulses were less than one percent. This could be the result of the fact that the SHB at UDRI is made of Inconel. Inconel's elastic moduli are relatively insensitive to temperature—decreasing by only 20 percent when heated to 700°C, according to Mil Handbook No. 5-C.

The thermocouple we used was an ungrounded probe (manufactured by Omega, probe No. SCASS-03236). We found that this probe is especially suited for our purposes because it can touch the specimen without causing triggering of the scope. Other probes, which were grounded, caused trigger problems because the specimen and the bars are part of the triggering circuit. The maximum reliable temperature with this probe is 927°C, according to the manufacturer. Also, due to the very small dimensions of the probe tip (diameter of 0.9 mm) temperature equilibrium with the specimen was fast. In order to estimate the uniformity of the temperature along the specimen during heating, we ran a few tests in which the temperature was checked at a few points along the specimen. We found that at an average temperature of 500°C the maximum difference between the points was less than 10°C. Thus we have assigned a value of ±2 percent to our temperature determination.

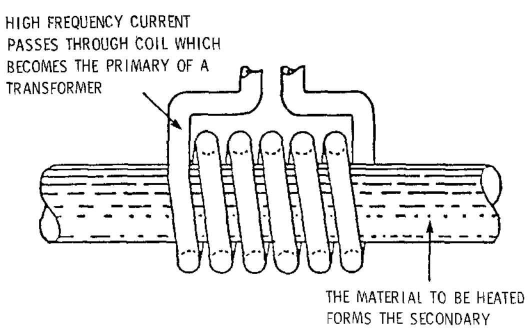

Fig. 1—The induction-coil heater

Results and Discussion

All experiments in this study were conducted at strain rates near 10^3 s^{-1}. This was done in order not to have too many changing parameters. Thus, the temperature of the specimen was the main parameter changing from room temperature to about 700°C, except for aluminum for which we reached only 450°C. We chose metals which show different behavior from the standpoint of rate sensitivity, work hardening, and ductility. Table 1 lists these metals with the property each one is representing. The W-2 tungsten alloy (manufactured by Kennametal) is very brittle and at room temperature our SHB could not resolve any measure of its strength because the failure was very early in the tension cycle. As we shall see later, at higher temperatures this material can be elongated much more and reasonable stress-strain curves could be extracted.

The ultra-high-carbon steel (52125) was given to us by R. Calgiuri of SRI International. He has shown[7] that this

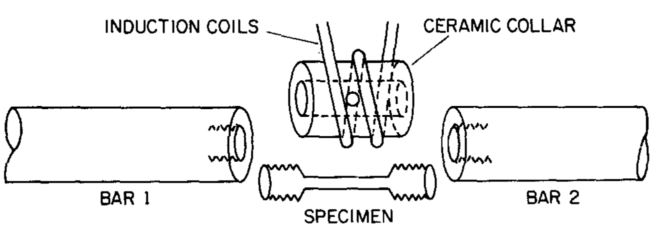

Fig. 2—Expanded view of experimental setup

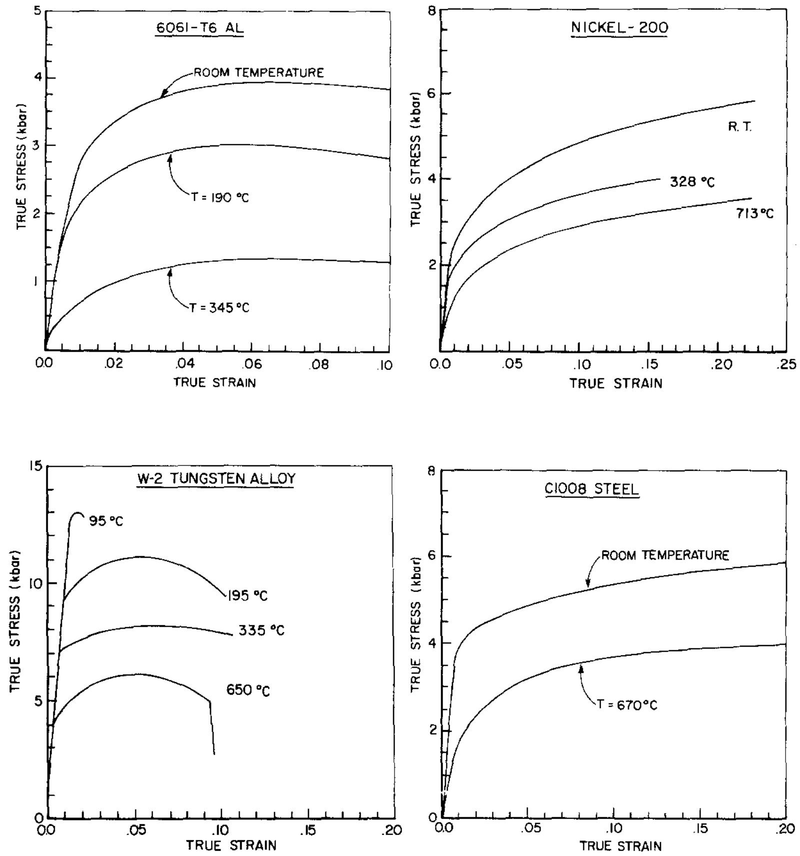

Fig. 3—Stress-strain curves at different temperatures

material behaves superplastically at high temperatures (near 500 °C) and low rates (10^{-4} s^{-1}). The analysis in Ref. 7 shows that this material should behave superplastically also at high strain rates (10^{3} s^{-1}) and temperatures near 700 °C. We reached 750 °C and did not observe very large plastic strains. Our intention is to run a second series of tests at higher temperatures (near 900 °C) in order to check for this superplasticity. Figure 3 shows typical stress-strain curves for the aluminum, nickel, tungsten and C-1008 steel specimens. As is clearly seen from this figure, the main characteristics of the room-temperature curve are repeated at the elevated temperatures except for the tungsten alloy. This material shows an increasing elongation for temperatures higher than 100 °C. Examination of the W-2 specimens showed brittle fracture characteristics with no necking for all specimens.

Plots of flow stress versus temperature, for the various metals tested, are shown in Fig. 4. Flow stresses were

TABLE 1—MATERIALS TESTED IN THIS STUDY

Material	Prominent Representative Properties
6061-T6Al	Elastic perfectly plastic behavior
Nickel 200	Appreciable work hardening
C-1008 Steel	Rate dependency
52125 Ultra-High-Carbon Steel	Expected to behave superplastically at 10^3 s^{-1} and temperatures near 700 °C
W-2 Tungsten Alloy (2.5% Ni-Cu-Fe)	Very brittle

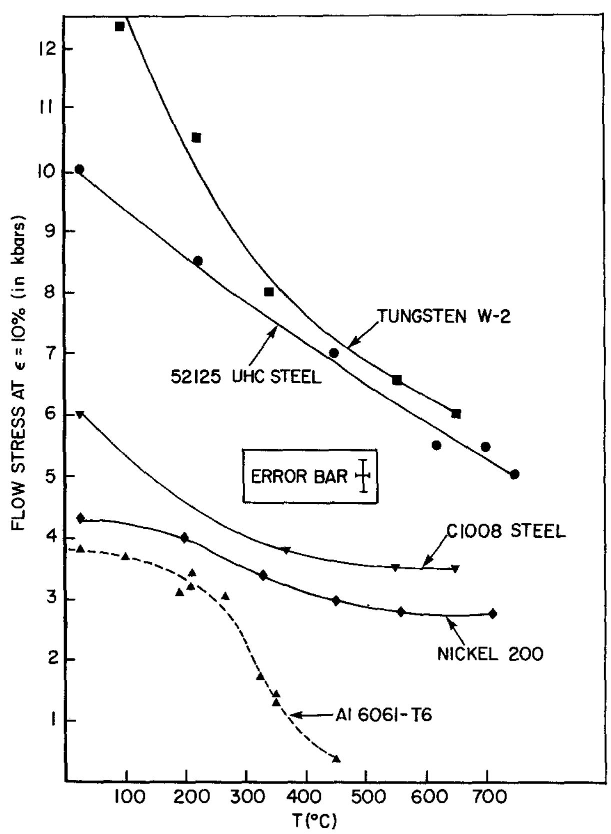

Fig. 4—Influence of temperature on the flow stress of the various metals tested in this study

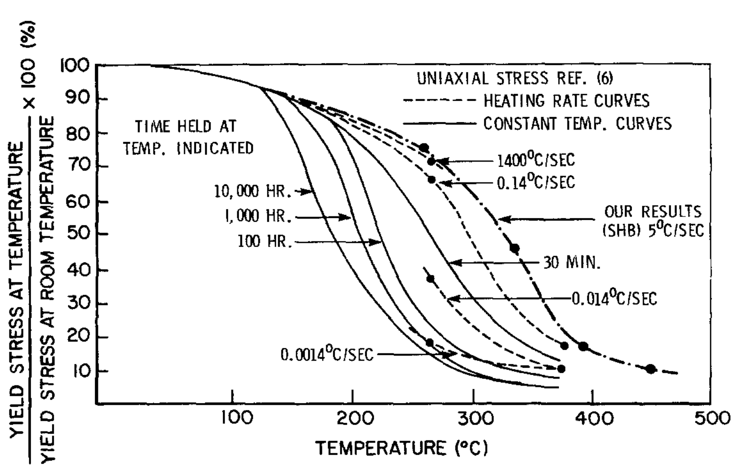

Fig. 5—Comparison of our results with those of Ref. 6 for 6061-T6 aluminum

taken at ten-percent strain except for the tungsten alloy (at five-percent). We see that for all materials tested in this study, the flow stress decreases substantially with test temperature. The S-shape of the flow stress versus temperature curve for 6061-T6 is very similar to that obtained by others; see Ref. 6 for example. It turns out that this S-shaped curve is shifted horizontally (towards the higher temperatures) when the heating rate is higher as can be seen in Fig. 5, which compares our results with those of Ref. 6 for 6061-T6 aluminum. Thus, this curve is not single valued, but depends on the heating rate. Our heating rates were about 5 °C/s. The uniaxial stress specimens in Ref. 6 were heated by resistive heating which can be used for both very low ($1 \cdot 10^{-3}$ °C/s) and very high ($1 \cdot 10^{3}$ °C/s) rates. All the curves in Ref. 6 show the S-shape including those which were obtained for specimens held at constant elevated temperature for prolonged periods of time. Scanning-electron-microscope pictures of the specimens in Ref. 6 show little change in the microstructure for heating rates above about 0.14 °C/s. However, at the slower rates, relatively large precipitates appear distributed uniformly throughout the grains and along grain boundaries. The fact that our curve (at 5 °C/s) is very close to their curves at higher rates can be considered as a strong validation of our heating technique with the induction coils. As for the 6061-T6 aluminum specimens themselves, it seems that heating rates faster than 0.14 °C/s do not change their mechanical properties as was suggested in Ref. 6.

Another comparison with published data can be made by considering the flow stress versus temperature curves for two stainless steels in Refs. 8 and 9. In both works, we see that at high strain rates the curves have a flat region which extends from about 300 °C to 700 °C. The reduction in flow stress from room temperature to 300 °C is by a factor of about two in these works. These features are also evident in our results for the C-1008 steel. The high carbon steel shows a somewhat different behavior in which the decrease is almost linear and does not show signs of saturation in this temperature range.

The sharp decrease in the flow stress of the tungsten alloy is not surprising. Considering Ref. 10, which reviews the mechanical properties of refractory metals, we see that the yield strength of these materials decreases dramatically when the temperature is raised to $0.2\,T_m$. Take T_m = 3680 K as the melting point of tungsten. We find that the temperature range 25 °C to 650 °C which we covered in this study is equivalent to $0.08\,T_m$ - $0.25\,T_m$, which is the temperature range where sharp changes in the yield strength are expected.

Conclusions

We describe a heating technique which is most appropriate to split-Hopkinson-bar experiments based on induction heating of metallic specimens. The two main advantages of this technique are (1) very high heating rates and (2) localized heated volume. We present experimental data in terms of stress–strain curves, for various metals up to about 700 °C. We find that these data are in good agreement with existing high-temperature high-strain-rate data for similar materials.

We do not attempt to analyze our data in terms of thermomechanical models. Such analyses can be found in the references cited. However, we do intend to do similar analysis in the future for several metals which are of special interest. Another objective is to extend the temperature range of the specimens to 1000 °C.

Acknowledgments

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