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9-23-76

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LA-6450-MS

Informal Report

UC-25

Reporting Date: July 1976

Issued: August 1976

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UNITED STATES
ENERGY RESEARCH AND DEVELOPMENT ADMINISTRATION
CONTRACT W-7408-ENG. 36

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**Printed in the United States of America. Available from
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road
Springfield, VA 22161
Price: Printed Copy \$3.50 Microfiche \$2.25**

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YIELD STRENGTHS OF TUNGSTEN-BASE COMPOSITES DETERMINED FROM BEND TESTS

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Eugene G. Zukas and David T. Eash

ABSTRACT

The variation in yield strength with either strain rate or temperature was determined for a number of tungsten-base composites by use of the simple three-point bend test. The yield strengths were comparable to those obtained in standard tensile tests. Additional studies on 1019 steel, either in the as-rolled or annealed condition, gave results in agreement with handbook values, as did two aluminum alloys. These results demonstrate that the bend test deserves wider acceptance in materials testing programs.

1. INTRODUCTION

Proper design for utilizing metals and alloys in structures which are subjected to complicated stress and temperature environments requires information not only of strength and ductility, but also the manner in which these properties change with strain rate and temperature. A number of testing techniques are available for obtaining such information, but the advantages of using the simple bend test are not fully appreciated, especially in instances where property trends must be established or where a selection must be made from a number of candidate materials. This report demonstrates some of the advantages of the bend test.

The small size and simple design of the test specimen reduces machining costs and material requirements. From these tests, the yield strength and the bend ductility can be obtained as a function of test temperature and as a function of strain rate. Strain rates to 10 min^{-1} (about 200 times that normally used during tensile

testing) can be used without special instrumentation. This test should be very useful for the selection of a material or heat treatment for some specific application. Metallographic examination at the bend is on material deformed in tension as well as on material deformed in compression. In some cases where fracture has occurred, metallography can reveal information about the mode of fracture.

II. EXPERIMENTAL TECHNIQUES

Bend tests on cast irons and steels have been used since the early 1920's.¹⁻³ A large number of mechanical arrangements have been tried. The bend fixture used here was designed similar to the one used by Warga et al.⁴ since this proved successful in obtaining data which established the ductile-brittle-transition-temperature (DBTT) for a number of refractory materials. Furthermore, this provided a direct comparison of test results obtained in this study with published results on other refractory metals and alloys. The bend fixture specifications and test conditions are shown schematically in Fig. 1. The bend specimens were 1.27 cm wide x 0.15 cm thick by 4.4 to 5.1 cm long (0.5" x 0.060" x 1.75-2.0"). Bending load was applied by a screw-driven Instron testing machine. Load vs time traces were obtained by a recorder synchronized with the testing machine. Reasonable results were obtained at crosshead rates of 25.4 cm/min (10"/min) and chart speeds of 127 cm/min (50"/min). However, recording pen lag was observed at crosshead rates greater than 25.4 cm/min.

Chart speeds were synchronized with crosshead motion. The strain rate was determined from this. As a calibration check, Young's modulus for 1019 steel was determined for a number of testing conditions. The values averaged about 5% low, roughly equivalent to values obtained in the standard tensile test. Testing at temperatures other than ambient was done by immersing the bend fixture with specimen in place for loading in a bath controlled at the desired temperature.

The mathematical formula for the maximum tension stress in a beam section during three-point loading is

$$S = \frac{3 L \ell}{2 b h^2}, \quad (1)$$

where L is the bending force in pounds, ℓ the distance between the supports in inches, b the specimen width in inches and h the specimen thickness in inches. However, it has long been recognized that the stress calculated by using Eq. 1 is much higher than that in the material because Eq. 1 is based on a stress distribution which increases linearly from the neutral axis to the outer fiber. A number of empirical correlations showed that if the stresses obtained by Eq. 1 were divided by 1.88, then the tensile strengths for brittle materials obtained from using bend tests and the modified stress equation were equivalent to those obtained from standard tensile tests. Thus, Eq. 1 can be modified to

$$S = \frac{0.8 L \ell}{b h^2} \quad (2)$$

to get the stress in psi, and

$$S = \frac{0.0055 L \ell}{b h^2} \quad (3)$$

to get the stress in MPa when measurements are made in pounds and inches. For loads in kilograms and lengths in centimeters, the equation becomes

$$S = \frac{0.07825 L \ell}{b h^2} \text{ MPa.} \quad (4)$$

For the bend fixture and specimens used in this study (L in pounds)

$$S = \frac{(0.0055) (L) (1.37)}{(0.5) (0.060) (0.060)} = 4.186L \text{ MPa} = 607L \text{ psi.} \quad (5)$$

The effect of surface finish was not evaluated, but to insure against premature fracture, the specimens were sanded through 600 grit SiC paper with the final sanding direction being longitudinal. Some of the specimens were then plated with either copper or nickel for use in a separate ductility study.^{5,6}

III. RESULTS

A series of tests were conducted on Grade 1019 rolled steel in the as-received condition and after it was given a one hour anneal at 1200 K followed by furnace cooling. The results are shown in Fig. 2. Note that the yield strength increases for this steel with increasing strain rate, and that the rate of increase is greater for the specimen in the rolled condition. These results are in agreement with results from experiments on armco iron done on a Cam Plastometer⁷ which showed that the yield strengths increased at a faster rate for greater amounts of plastic strain. The increase in the stress of the lower yield point was at the same rate as that of the upper yield strength.

The strain rate effect on face-centered-cubic materials is quite different from that on bcc materials.^{8,9} Two aluminum alloys were tested at strain rates of 0.02 to 10 min⁻¹. The yield strength of the harder aluminum alloy (6061-T6) increased much more rapidly than did the soft (1100-H14) at high strain rates, in agreement with the strain rate effects on pure aluminum.¹⁰⁻¹³ These results are shown in Fig. 3.

Two commercial liquid-phase sintered W-base composites (G-1100* and W-2**) were bend-tested at a strain rate of 1 min⁻¹ from almost 200 K to 373 K for the W-2, and to 473 K for the G-1100. The yield strengths as a function of testing temperatures are shown in Fig. 4. Both composites failed in a brittle manner at 75 K.

The tensile strengths as a function of test temperature are shown in Fig. 5 for a base line 95 wt% W-3.5 wt% Ni-1.5 wt% Fe liquid-phase sintered composite and two similar composites where a small part of the tungsten was replaced by rhenium. The yield strengths decrease gradually with increasing test temperature with the rate of decrease being a little lower for the composites containing rhenium. The results from tests conducted over a small temperature range can be represented reasonably by a straight line plot, whereas the plot of the change over a larger temperature difference would probably be slightly concave upward, as in Fig. 4.

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**Kennametal, Inc., Latrobe, PA.

Fig. 1
Schematic representation of the bend test. a) Specimen ready for test, b) loading in the elastic range, c) latter stages of a normal test, and d) completed test without fracture.

Fig. 2
Yield strength as a function of strain rate for 1019 steel in the as-rolled and annealed conditions from bend tests. Tests run at 298 K.

Fig. 3
Yield strength as a function of strain rate for 1100-H14 and 6061-T6 aluminum from bend tests. Tests run at 298 K.

Fig. 4
Yield strength as a function of temperature for two commercial liquid-phase-sintered W-base composites as determined from bend tests.

It should be noted that these specimens were plated with about 0.06 mm of either copper or nickel for separate low temperature ductility studies,^{5,6} but yield strength results at 298 K for both plated and unplated specimens gave identical values. A similar series of tests was run on specimens where part of the tungsten was replaced by platinum instead of rhenium. The results are shown in Fig. 6. For these composites, the influence of temperature on yield strength appeared to be slightly greater than for the rhenium composites, but otherwise were essentially the same.

Several tungsten-base composites were tested over a range of strain rates at 298 K, and the data extrapolated to that obtained for several similar tungsten base composites tested by shock loading. For the shock loading experiments, the elastic wave pressure was considered to represent the dynamic yield strength, and the longitudinal elastic wave velocity was used as the strain rate. The results are shown in Fig. 7. Surprisingly, the extrapolation is fairly reasonable, especially when one considers that the rate is over nine orders of magnitude. The yield strength (elastic wave pressure) is about three times that obtained for rates used in the standard tensile tests, in very good agreement with results published earlier¹⁴ on a number of entirely different materials. Such plots are valuable when selecting materials for use at high loading rates where lower strength materials having greater ductility might prove more satisfactory. It also cautions against constant stresses just slightly below the "usual yield strength" where deformation or creep would take place. For the plot in Fig. 7, the yield strength for any particular strain rate can be calculated from the equation

$$Y.S. = 483 + 179 \log\left(\frac{\dot{\epsilon}_2 \text{ sec}^{-1}}{1 \times 10^{-4} \text{ sec}^{-1}}\right) \text{ MPa} \quad (6)$$

or

$$Y.S. = 70,000 + 26,000 \log\left(\frac{\dot{\epsilon}_2 \text{ sec}^{-1}}{1 \times 10^{-4} \text{ sec}^{-1}}\right) \text{ psi} \quad (7)$$

where $\dot{\epsilon}_2$ is the anticipated strain rate. For these composites then, the yield strength for the usual tensile test (0.05 min^{-1} or $8.33 \times 10^{-4} \text{ sec}^{-1}$) would be 648 MPa (93,900 psi) and for the bend test (1 min^{-1} or $1.67 \times 10^{-2} \text{ sec}^{-1}$), it would be 881 MPa (127,800 psi).

Fig. 5

Yield strength as a function of temperature for a 95 wt% W-3.5 wt% Ni-1.5 wt% Fe liquid-phase-sintered composite, and for two similar composites where part of the tungsten was replaced by rhenium.

Fig. 6

Yield strength as a function of temperature for a 95 wt% W-3.5 wt% Ni-1.5 wt% Fe liquid-phase sintered composite, and for two similar composites where part of the tungsten was replaced by platinum. Data from bend tests.

Fig. 7

Yield strength as a function of strain rate for a few typical tungsten-base composites obtained from bend tests and extrapolated to the elastic wave pressure and longitudinal sound velocity for several similar composites tested by shock loading. Tests at 298 K.

Plots of yield strength vs strain rate were not linear for the aluminum alloy tests indicating that extrapolations may not be reliable, especially for non bcc materials.

IV. DISCUSSION

The results of bend tests presented here demonstrate that the yield strengths of materials as either a function of strain rate, temperature or composition can be determined readily from such tests. Bend ductilities and DBTT can be determined during the same series of experiments. Furthermore, metallography is possible on single etched surfaces which include both deformation in compression and deformation in tension. Yield strength data are comparable to that obtained in the standard tensile test, yet the specimen size and shape required are conservative of material and much more economical insofar as machining costs are concerned. Therefore, the bend test should be utilized during routine testing programs. There are several shortcomings to this test. For example, elastic moduli determined from this test are no better than those determined from the standard noninstrumental tensile test. Also, the ultimate strength is not a reliable measurement since many of the mechanical features such as roll slippage and friction affect this measurement. Also, the bend equations are not valid in the plastic region. However, this is usually an imaginary disadvantage since structures generally are not designed for use in places where they must undergo extensive plastic deformation. To further complicate design criteria, the ultimate strength varies with temperature, strain rate, and environmental conditions.

V. CONCLUSIONS

The bend test is simple to conduct, conservative of material, and specimens are less expensive to machine. Yield strengths as a function of strain rate, temperature, and composition are readily measured. Bend ductilities and the DBTT can also be determined. Metallographic examination includes material deformed in tension as well as in compression. In many cases, fracture modes are

discernable. In view of these advantages, the bend test merits wider usage on a routine basis.

ACKNOWLEDGMENTS

The authors express their thanks to members of CMB-6 for their assistance in specimen manufacture, to John E. Hockett of WX-5 for stimulating discussions and encouragement, and to R. N. R. Mulford and R. D. Bard for their support of this program.

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