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LARGE STRAIN COMPRESSION OF TWO TUNGSTEN ALLOYS AT VARIOUS STRAIN RATES

JOHN L. GREEN and PAUL MOY
MATERIALS DYNAMICS BRANCH

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ABSTRACT

This report describes the material characterization of two tungsten alloys in terms of their modulus of elasticity, yield stresses, and true stress-true strain curves. These alloys are W2 (Kennametal) with 97.2% tungsten and X21 (Teledyne, Firth, and Sterling) with 93% tungsten. Both alloys were compressed to strains between 40% and 75%, and at strain rates between 0.0001/sec and 3000/sec. The experiments were conducted in the Medium Strain Rate Machine (MSRM) and Split Hopkinson Pressure Bar (SHPB) facilities at the U.S. Army Materials Technology Laboratory (MTL). The effect of strain rate was ascertained for each alloy and a comparison conducted on their stress-strain relationships. Metallographic examinations of the microstructure were conducted on both tungsten alloys to determine if adiabatic shear bands had developed. Zones of shear deformation were observed but were attributed to frictional effects at the ends of specimens. At large deformations, frictional effects cause specimen barrelling and a three-dimensional stress state. Annular grooves were machined into the ends of the specimens and, in addition, Teflon™ sheets provided lubrication thereby eliminating frictional effects. Both alloys are strain rate sensitive; however, the W2 alloy is somewhat more sensitive at higher strain-rates. No adiabatic shear bands were observed and shear deformation due to frictional effects was eliminated by using the modified specimen and Teflon™ sheeting.

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INTRODUCTION

Dynamic compressive property values for tungsten alloys are essential for the development and evaluation of advanced anti-armor systems. This report describes the material characterization of W2 (Kennametal) with 97.2% tungsten and X21 (Teledyne, Firth, and Sterling) with 93% tungsten. Presently available manufacturer's chemical and material properties data for the alloys are given in the Appendix in Tables A-1 and A-2. Previous efforts at the U.S. Army Materials Technology Laboratory (MTL) have been directed towards the comparison of various tungsten alloys by performing ballistic penetration experiments.¹ The development of anti-armor systems is a complex process which requires computer simulations of various ballistic events. These simulations are conducted using finite element analysis (FEA) codes which must take into account the dynamic nature of the event. The input dynamic properties for these analyses must often be experimentally obtained under dynamic loading conditions. The controlled dynamic loading of candidate materials for ballistic applications were conducted using the Medium Strain Rate Machine (MSRM) and Split Hopkinson Pressure Bar (SHPB) facilities at MTL.^{2,3} This study investigates the compressive stress-strain histories of these tungsten alloys subjected to compressive strains up to 70% at strain rates between 0.0001/sec and 3000/sec.

When barrelling occurs during a compression test, a nonuniform strain distribution is generated resulting in the development of a triaxial stress condition and test data is no longer considered valid. By maintaining a uniaxial state of stress, the external measurements of force can be directly related to the stress in specimen. A uniaxial state of stress at large deformations was maintained by using a modified compression specimen in addition to lubrication of the ends. The compression specimen was modified by machining a series of shallow annular grooves in specimen ends and Teflon™ tape provided lubrication at the specimen ends. The lubrication virtually eliminated friction at the specimen ends resulting in negligible barrelling. By controlling the amount of compressive deformation and rate of compression we were able to determine the effect of dynamic loading on the tungsten alloys.

The role of adiabatic shear band development in ballistic events has been reported to significantly effect materials performance.^{4,5} The narrow shear bands are concentrations of large deformations at high temperatures. These high temperatures can often cause a phase transformation in the material, and these resulting narrow bands have often been referred to as transformation bands. This study examined the microstructure of several specimens for the development of shear bands. Two specimens from each test condition were cross-sectioned and polished for metallographic examinations under a light microscope at a magnification of 100X. Orientation of deformed grains relative to loading axis was observed; a localized band of grains oriented at 45° to loading axis would be proof of an adiabatic shear band. This examination would then determine if the modified compression specimen and the use of Teflon™ lubricant leads to the elimination of adiabatic shear bands under the applied loading conditions.

1. DOWDING, R. J., TAUER, K. J., WOOLSEY, P., and HODI, F. S. *The Metallurgical and Ballistic Characterization of Quarter-Scale Tungsten Alloys Penetrators*. U.S. Army Materials Technology Laboratory, MTL TR 90-91, May 1990.
2. GREEN, J. L., EMSLI, J. F., and CHOU, S. C. *The Application of Laser Speckle Interferometry to Measure Strain at Elevated Temperatures and Various Loading Rates*. U.S. Army Materials Technology Laboratory, MTL TR 90-23, May 1990.
3. ROBERTSON, K. D., CHOU, S. C., and RAINEY, J. H. *Design and Operating Characteristics of a Split Hopkinson Pressure Bar Apparatus*. U.S. Army Materials Technology Laboratory, AMMRC TR 71-49, November 1971.
4. MESCALL, JOHN F., and ROGERS, HARRY. *Role of Shear Instability in Ballistic Penetration*. U.S. Army Materials Technology Laboratory, MTL TR 89-104, December 1989.
5. ROGERS, H. C. *Adiabatic Plastic Deformation*. *Ann. Rev. Mat. Sci.*, 1979, p. 283-311.

EXPERIMENTAL PROCEDURE

All experiments conducted were uniaxial compression using a modified specimen and Teflon™ lubrication between specimen and the loading platens. A total of 21 tungsten alloy specimens were tested according to the test matrix in Table 1. For each material there were at least three successful experiments conducted at 0.0001 sec^{-1} , and 2 sec^{-1} , at $3 \times 10^3 \text{ sec}^{-1}$ there were two successful experiments for each material.

Table 1. TEST MATRIX FOR W2 AND X21 TUNGSTEN ALLOYS

Number of Specimens	Material	Test Condition	Strain Rate (/sec)	Testing Apparatus	Specimen End Condition	Lubricating
4	W2	Compression	0.0001	MSRM	Annular Grooves	Teflon™
4	W2	Compression	2	MSRM	Annular Grooves	Teflon™
3	W2	Compression	3000	SHPB	Annular Grooves	Teflon™
4	X21	Compression	0.0001	MSRM	Annular Grooves	Teflon™
4	X21	Compression	2	MSRM	Annular Grooves	Teflon™
2	X21	Compression	3000	SHPB	Annular Grooves	Teflon™

To obtain experimental data between strain rates of 0.0001 sec^{-1} and $3 \times 10^3 \text{ sec}^{-1}$ two test machines were required. The two facilities used for testing of the alloys were the MSRM and the SHPB facilities. The operating strain rate ranges for the machines are 0.0001 sec^{-1} to 50 sec^{-1} for MSRM, and 10^2 sec^{-1} to 10^4 sec^{-1} for SHPB. Although the results from both test machines are stress-strain curves at various strain rates, different physical quantities are measured. For the MSRM, load, specimen strain, crosshead displacement, and time are acquired; for the SHPB, elastic strain due to a stress pulse in the input and output bars was acquired. These sets of data are captured using digital oscilloscopes then transferred to a computer for analysis. From the initial analysis, engineering stress, engineering strain, strain rate, and time are obtained. Post mortem measurements of the compressed specimen's top middle and bottom diameters were then made and used to determine if any barrelling has occurred. Test results were considered invalid if diametral measurements vary more than 0.01 inch. After verification that no barrelling has occurred, a more detailed analysis of experimental data is conducted to obtain true stress-true strain results.

Analysis of experimental data assumed that the volume of the material remained constant during plastic deformation.⁶ Using the assumption of incompressibility, and the fact that negligible barrelling of specimen occurred, true stress-true strain results were obtained. The original volume of each specimen was calculated using Equation 1.

$$V_0 = A_0 L_0 \tag{1}$$

where:

- V_0 = original volume (cm^3)
- A_0 = original area (cm^2)
- L_0 = original length (cm)

6. CHOU, S. C., and GREEN, J. L. *Compression Test of Metals to Large Strains. Analytical and Testing Methodologies for Design with Advanced Materials.* G. C. Shi, J. T. Pindera, and S. V. Hoa, eds., 1988, p. 113-125.

The instantaneous volume of each specimen was calculated using Equation 2.

$$V = A L \quad (2)$$

where: V = instantaneous volume (cm^3)
 A = instantaneous area (cm^2)
 L = instantaneous length (cm)

The instantaneous area of each specimen was calculated using Equation 3.

$$A = (A_0 L_0)/L \quad (3)$$

where: A = instantaneous area (cm^2)
 A_0 = original area (cm^2)
 L_0 = original length (cm)
 L = instantaneous length (cm)

The true stress of each specimen was calculated using Equation 4.

$$\sigma = P/A \quad (4)$$

where: σ = true stress (MPa)
 P = load (kg)
 A = instantaneous area (cm^2)

The true strain of each specimen was calculated using Equation 5.

$$e = \ln(L/L_0) \quad (5)$$

where: e = true strain
 L_0 = original length (cm)
 L = instantaneous length (cm)

The true stress-true strain results for each experiment are grouped according to strain rate, then an average true stress-true strain curve calculated. The method by which the raw data was acquired makes calculation of the average true stress-true strain curve a very simple procedure. For a given strain rate all the test data is acquired at the same sampling rate; therefore, all test data is equally spaced in time and simple arithmetic was used to average data for each time interval.

Medium Strain Rate Machine Facility (MSRM)

Tests on the MSRM were conducted at speeds ranging from 0.0001 sec^{-1} to 2 sec^{-1} . All testing was conducted at room temperature (70°F). The MSRM machine has a 140,000 pound static load capacity. There are two operating modes; the closed loop mode, and the open loop mode. In the closed loop mode, the MSRM has the same characteristics typical of servo-hydraulic controlled test machines. A strain/load/displacement rate up to 1 sec^{-1} was achieved. In the open loop mode, the hydraulic fluid is replaced by nitrogen gas. A fast-acting valve is used to release the gas from the top or bottom of an actuating piston creating a pressure differential which moves the piston. The loading rate in the open loop mode is controlled by the gas pressure, stroke of the piston, and the orifice size selected for the fast acting valve. A nominal rate of up to 50 sec^{-1} can be achieved depending on the ductility of the specimen. Stress and strain measurements were obtained through the use of load cells, strain gages, and linear variable differential transformer (LVDT). The strain gages are used to measure strains up to 5%. The LVDT was used to measure displacements above 5% strain. The LVDT displacement measurements, together with the specimen's gage length and two correction factors, were used to obtain strains greater than 5%. First, the LVDT data was corrected for compliance of test fixtures by measuring the displacement of fixturing without specimen. The second correction was to shift the LVDT curve to account for groove distortion, the curves were shifted 3% to 5% strain depending on groove depth. A computer with a fast data acquisition and a digital oscilloscope were used to control the MSRM and record load, strain, displacement, and time during testing.

Split Hopkinson Pressure Bar Facility

High strain rate compression experiments were conducted by means of the SHPB. Two different bar configurations were used to generate the high strain rate compression data. The bar configuration used to obtain the W2 results had 20-inch input and output bars and used a three-strain gage system. The bar configuration used for obtaining data on the X21 material consisted of five-foot long input and output bars and a two-gage system. The basic principle underlying both SHPBs is that an elastic striker bar is propelled by pressurized nitrogen gas to impact an elastic input bar. A compressive stress wave is then produced and propagates down the input bar. At the input bar/specimen interface the stress wave is partly reflected and partly transmitted into the specimen. The input bar is chosen to be elastic and of higher impedance than the specimen. This results in a reflected wave that is tensile in nature. The compressive wave transmitted through the specimen is transmitted into the output bar as a compressive wave. By measuring the magnitudes of strains generated in the input bar due to the initial compressive wave and reflective tensile wave, and in the output bar due to transmitted compressive wave as a function of time, it is possible to obtain a stress-strain profile for the specimen at strain rates up to $10^4/\text{sec}$.

Specimen Design

Rastegay compression specimens, designed to incorporate lubrication at their ends, have been used by the author in previous compression studies.⁶ All specimens in this report were solid right cylinders with annular grooves in the specimen ends. The specimen lengths and diameters varied depending on the test apparatus. The nominal values of specimen length and diameter for each test condition are given in Table 2.

Table 2. NOMINAL DIMENSIONS FOR W2 AND X21 TUNGSTEN ALLOY SPECIMENS

Material	Test Apparatus	Strain Rate (/sec)	Specimen Length (in.)	Specimen Diameter (in.)
W2	MSRM	0.0001	0.5	0.5
W2	MSRM	2	0.5	0.5
W2	SHPB (20 in. Bars)	3000	0.375	0.375
X21	MSRM	0.0001	0.5	0.5
X21	MSRM	2	0.5	0.5
X21	SHPB (60 in. Bars)	3000	0.125	0.25

This specimen is an improvement over the Rastegay compression specimens since it is more stable when subjected to dynamic loading and is also easier to manufacture because it requires less removal of material. The manufacture of the specimen involves first grinding the ends flat and parallel within 0.0001 inch, then grooves are cut in ends of the cylinder, in accordance with Figure 1, for the purpose of trapping Teflon™ to minimize the frictional effects that occur at the specimen ends. Strain gages used in these tests were post-yield gages capable of measuring strain to 10%. These gages were placed along the loading axis 180° apart. These gages were used to measure strain as well as a check for bending in the specimen as a result of crosshead misalignment. The adhesive used was EPY-150.

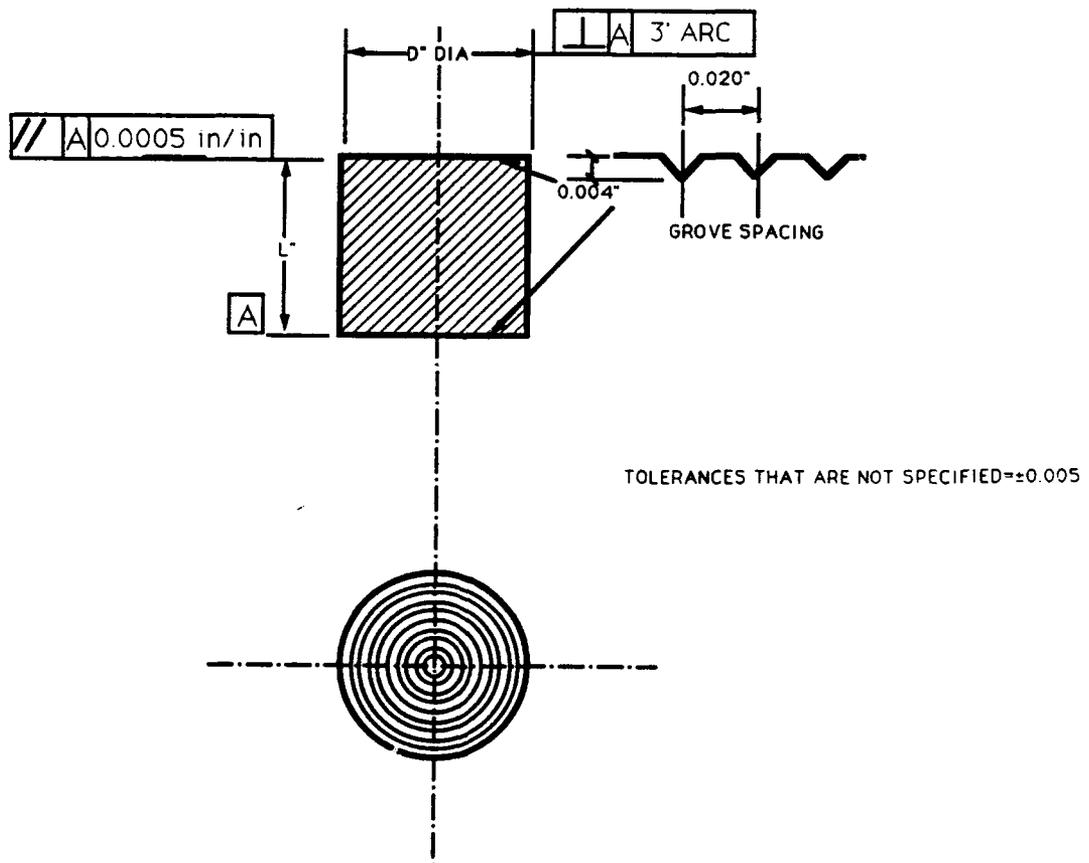


Figure 1. Drawing of tungsten alloy compression specimen with annular grooves in specimen ends.

RESULTS AND DISCUSSION

The W2 and X21 compression average true stress-true strain curves for strain rates are 10^{-4} sec^{-1} , 2 sec^{-1} , and $3 \times 10^3 \text{ sec}^{-1}$ are shown in Figures 2 and 3, respectively. The average yield points (0.2% offset) and modulus of elasticity are listed in Table 3 for all specimens tested at strain rates of 10^{-4} sec^{-1} and 2 sec^{-1} .

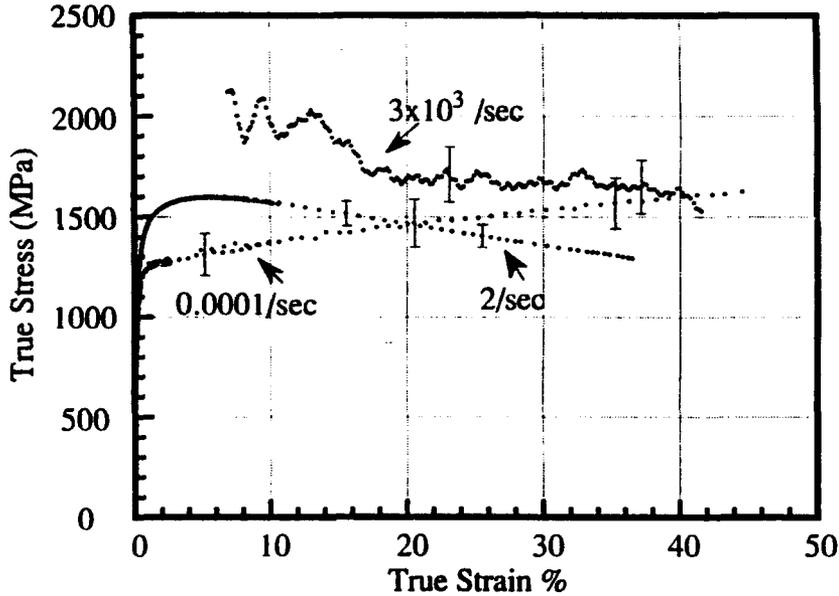


Figure 2. Average true stress-true strain compression results of 97.2% W alloy (Kennametal's W2) at strain rates between 0.0001/sec and 3000/sec.

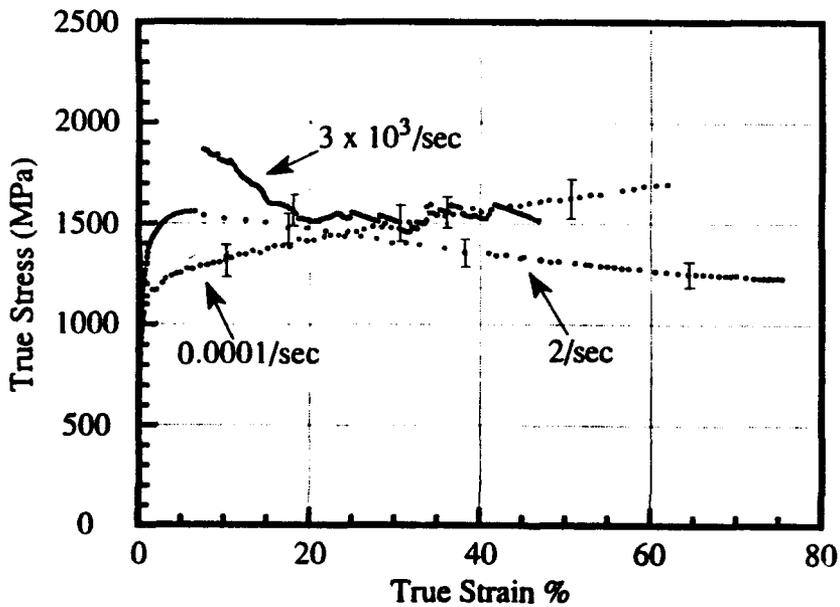


Figure 3. Average true stress-true strain compression results of 93% W alloy (X21) at strain rates between 0.0001/sec and 3000/sec.

Table 3. MECHANICAL PROPERTIES OF W2 AND X21 TUNGSTEN ALLOYS

Strain Rate (/sec)	97.2% W (W2)		93% W (X21)	
	Modulus of Elasticity (GPa)	Yield Point (MPa)	Modulus of Elasticity (GPa)	Yield Point (MPa)
0.0001	346.8	1151	366.1	1034
2	353.7	1334	359.9	1204

The strain rate sensitivity of both alloys is clearly demonstrated by a 17% to 20% increase in yield point when the strain rate is increased from 0.0001 sec^{-1} to 2 sec^{-1} . This is evident from Figures 2 and 3. At large strains and dynamic loading rates, thermal softening decreases the strength of both alloys to the point where the 2 sec^{-1} and $3 \times 10^3 \text{ sec}^{-1}$ flow stresses are less than the 0.0001 sec^{-1} flow stress. The oscillations in the first 10% strain of the W2 $3 \times 10^3 \text{ sec}^{-1}$ data in Figure 2 are caused by vibrations in bars. This is commonly referred to as ringing, and these large amplitude oscillations normally occur within 1% to 2% strain for experiments with a total strain of about 10%. Since these SHPB experiments were conducted to large strains; i.e., 45% strain, the ringing was experienced at strains up to 10%. SHPB test data is only considered valid when a constant strain rate is maintained, implying that the stress distribution and deformation within specimen is uniform. Any data that does not meet this constant strain rate requirement is discarded. The W2 and X21 SHPB data less than 6% strain and greater than 45% strain did not meet the constant strain rate requirement and was discarded. Figures 4, 5, and 6 are a comparison of W2's and X21's true stress-true strain curves at strain rates of 10^{-4} sec^{-1} , 2 sec^{-1} , and $3 \times 10^3 \text{ sec}^{-1}$, respectively. When comparing W2 and X21 at strain rates of 10^{-4} sec^{-1} and 2 sec^{-1} , the scatter in data make the two material's true stress-true strain curves indistinguishable. At a strain rate of $3 \times 10^3 \text{ sec}^{-1}$ there is some overlap of the W2 and X21 true stress-true strain scatter bands, but enough of a difference exists between the alloys average true stress-true strain curves to raise the issue that possibly at even higher strain rates this trend may be more pronounced. Whether the difference in the high strain rate data is due to strain rate affects or thermal softening will require further investigation.

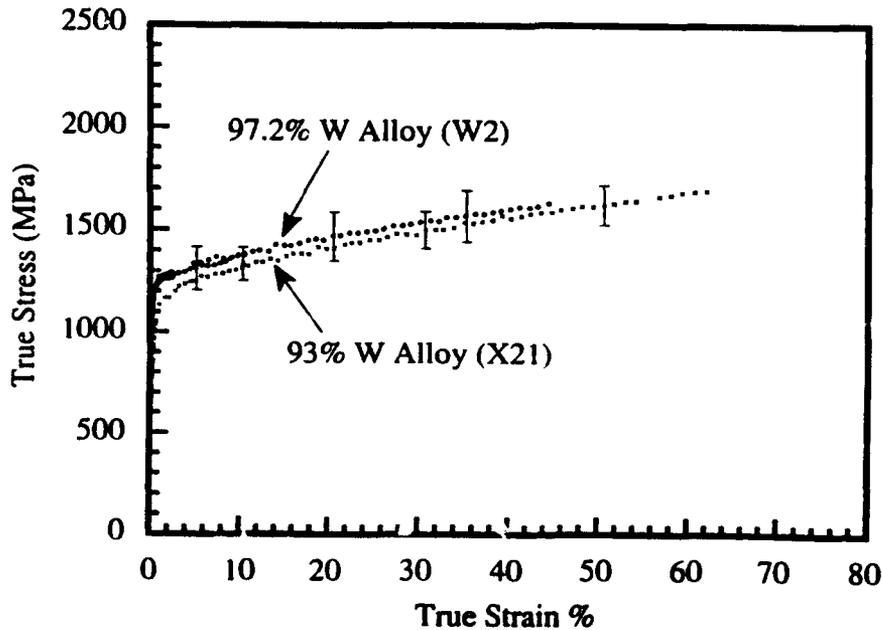


Figure 4. Comparison of average true stress-true strain compression results of 97.2% W alloy (Kennametal's W2) and 93% W alloy (X21) at a strain rate of $0.0001/\text{sec}$.

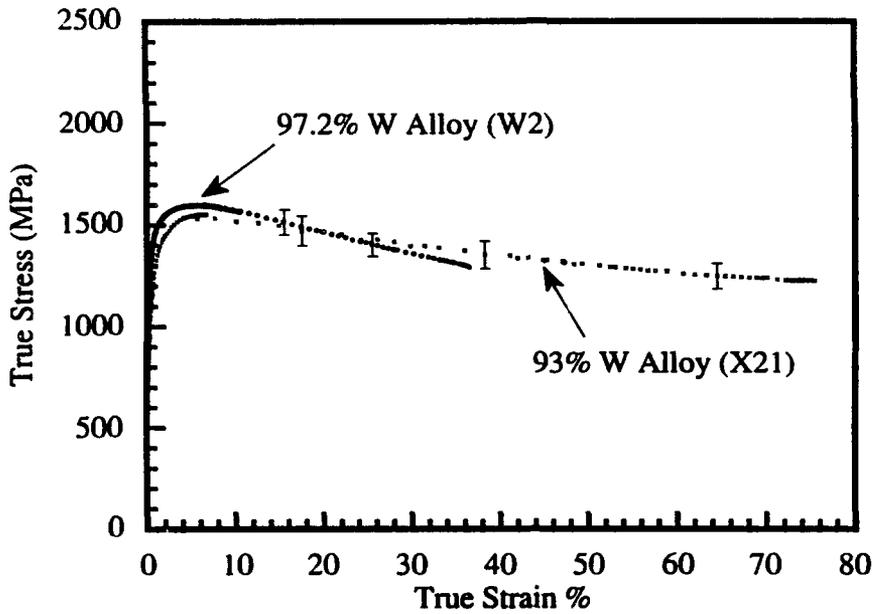


Figure 5. Comparison of average true stress-true strain compression results of 97.2% W alloy (Kennametal's W2) and 93% W alloy (X21) at a strain rate of 2/sec.

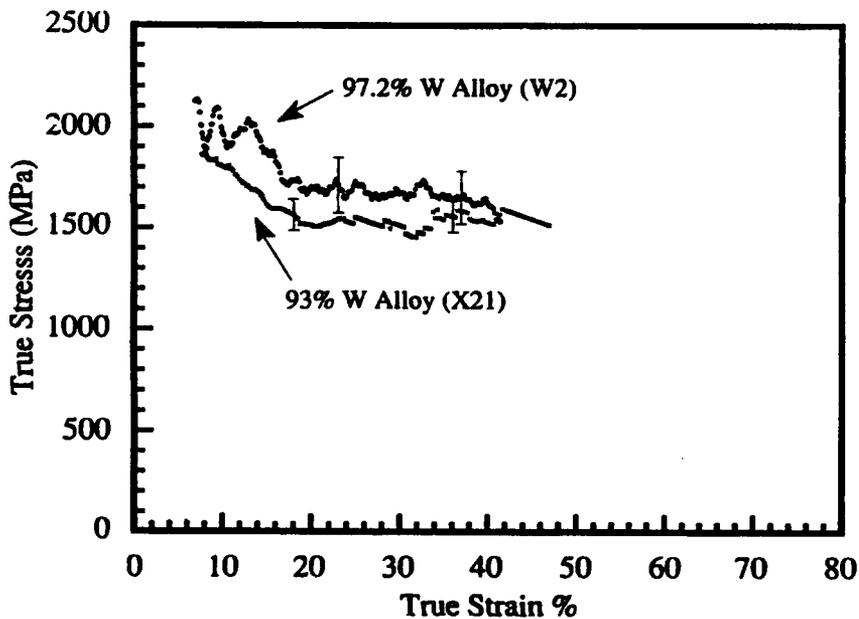


Figure 6. Comparison of average true stress-true strain compression results of 97.2% W alloy (Kennametal's W2) and 93% W alloy (X21) at a strain rate of 3000/sec.

A microstructural examination of the test specimens was made after the compression tests were performed to determine if adiabatic shear bands were present. Specimens were cross-sectioned parallel to the loading direction. Two specimens from all six test conditions were examined to determine if adiabatic shear bands were present. After observations of the W2 and X21 tungsten alloy specimen's microstructure, no adiabatic shear bands were observed. A comparison of barreled and nonbarreled specimen's microstructures was made. Figure 7 is a photomicrograph of the as-received (before testing) W2 and X21 tungsten alloys. Observations

of these photomicrographs show that the W2 alloy has a much coarser grain structure, the W2 tungsten grains are three to four times larger than the X21 tungsten grains. Although there is a large difference in grain size between the two alloys, there was no difference between these alloys' mechanical properties. All photomicrographs were taken at a magnification of 100X. Figure 8 is a photomicrograph of specimens compressed to ~45% strain at a strain rate of 2 sec^{-1} . Due to breakdown of the lubrication system some specimens did barrel. Figures 9 and 10 are composite pictures of two photomicrographs comparing slightly barrellled and non-barrellled specimens of W2 and X21. These were also taken at a magnification of 100X. Previous studies indicate that when zones of shear deformation are developed in barrellled specimens a nonuniform stress distribution develops and the test is invalid.⁷ This small amount of barrelling subjects the specimen to both tension and compression causing areas of shear deformation at a 45° angle to the specimen ends. The comparison of barrellled and nonbarrellled specimens in Figures 9 and 10 shows that the area of shear deformation, is due to breakdown of the lubrication system during the test and not due to a material characteristic. The necessary precautions must be taken to avoid specimen barrelling which could lead to misinterpretation of material characteristics.

CONCLUSION

The results show there is no statistical justified difference between W2's and X21's compressive true stress-true strain histories at strain rates between $10^{-4}/\text{sec}$ and $3 \times 10^3/\text{sec}$. Both alloy's yield point increased with strain rate. Due to the large plastic strain and dynamic loading conditions, thermal softening decreases the strength of both alloys with increasing strain.

The results show that compression specimens with annular ring grooves in combination with Teflon™ tape lubrication were successfully used to achieve large plastic deformations with negligible barrelling. True strains between 35% to 70% were obtained.

Microstructural observations were made of W2 and X21 tungsten alloy specimens compressed to large strains at strain rates between $10^{-4}/\text{sec}$ and $3 \times 10^3/\text{sec}$. No shear bands were observed in any of the specimens. Zones of shear deformation were observed in specimens that were subjected to nonuniform deformation; i.e., barrelling. Specimens that exhibited no barrelling did not have any zones of shear deformation.

When using compression testing methods to relate shear band development and stress-strain histories, specimen end conditions must be modified to eliminate friction. Without a frictionless end condition barrelling will occur resulting in two problems. First, the axial stress-strain information is not relevant to the actual stress-strain distribution within specimen. Second, generation of shear zones, and possibly adiabatic shear bands, can no longer be related to the materials measured stress-strain histories. For these reasons the authors recommend using a torsional Hopkinson bar test method when trying to generate adiabatic shear bands and relate them to a material's stress-strain history.

ACKNOWLEDGMENTS

The authors wish to thank Dr. Tusit Weerasooriya for providing the unpublished 93% tungsten alloy 3000/sec results and specimen photomicrographs. The authors also wish to thank him for his valuable technical discussions on all aspects of this report, and the motivation to publish this work. The authors wish to thank Messrs. W. Crenshaw and W. Bethony for their assistance and suggestions in preparing this report, and Mr. D. Stewart for making and preparing compression specimens.

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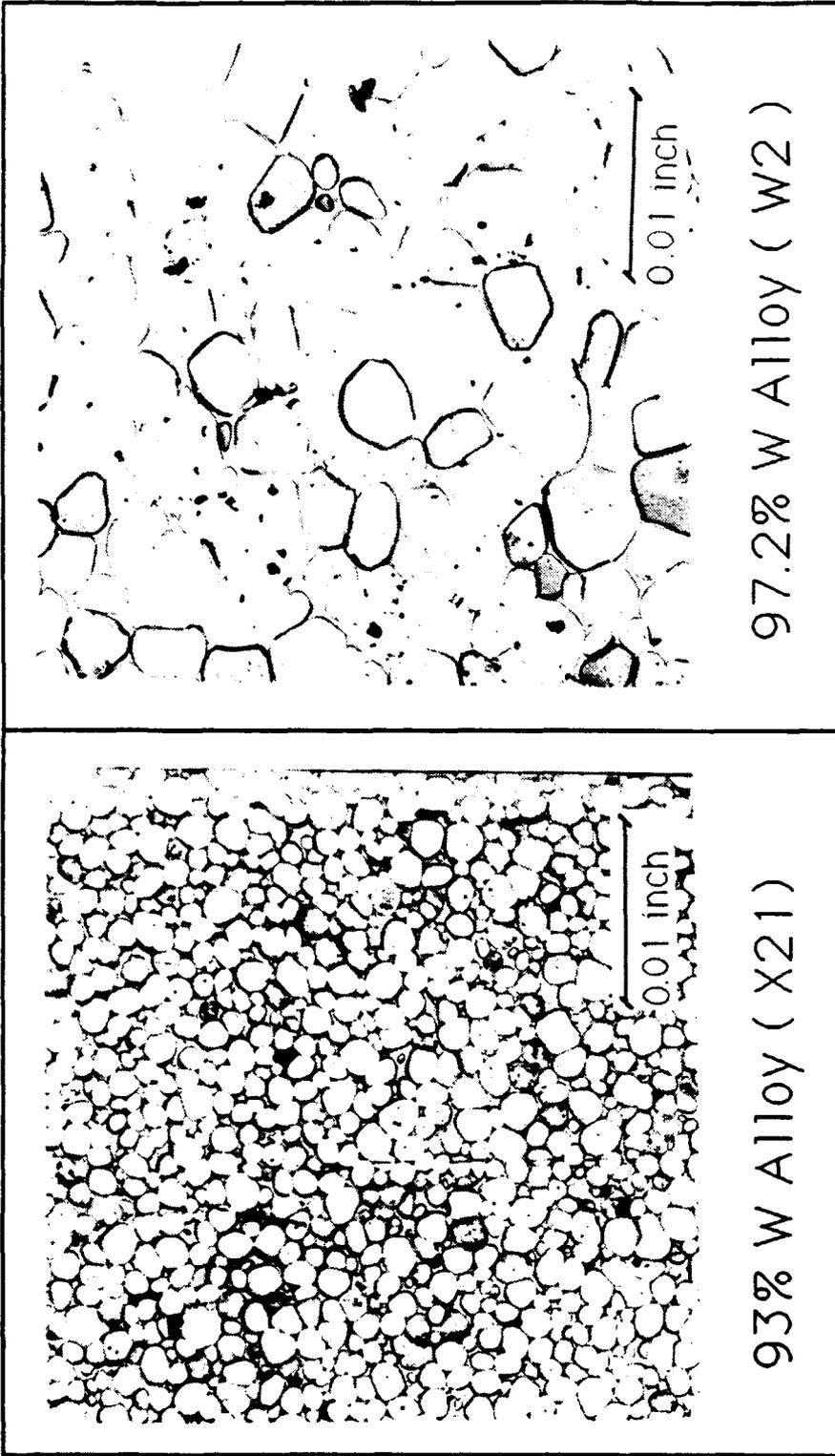


Figure 7. Microphotographs of 93% W alloy (X21) and 97.2% W alloy (W2), as-received, at a magnification of 100X.

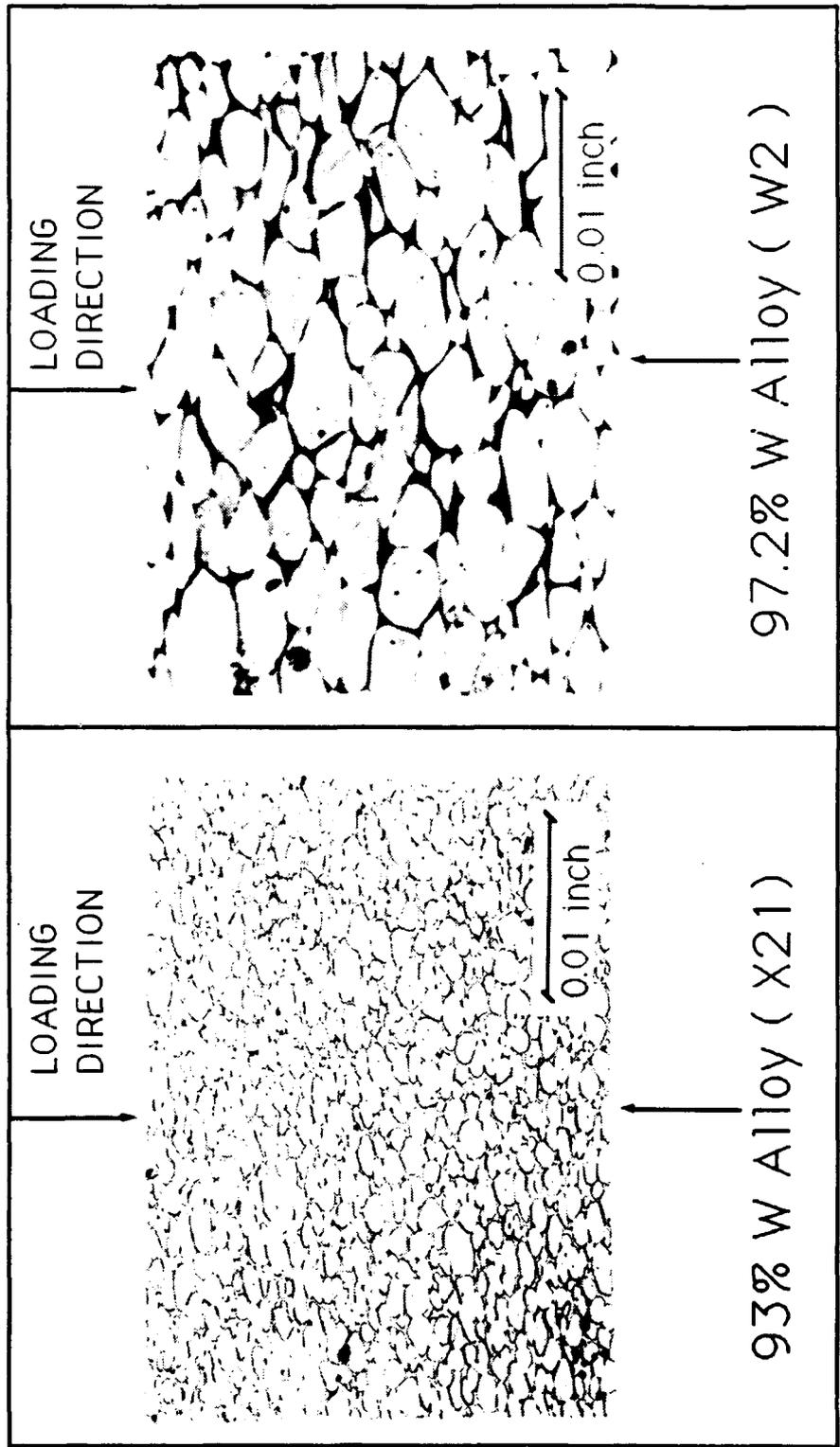


Figure 8. Microphotographs of 93% W alloy (X21) and 97.2% W alloy (W2), compressed to 45% strain and a strain rate of 2/sec, at a magnification of 100X.

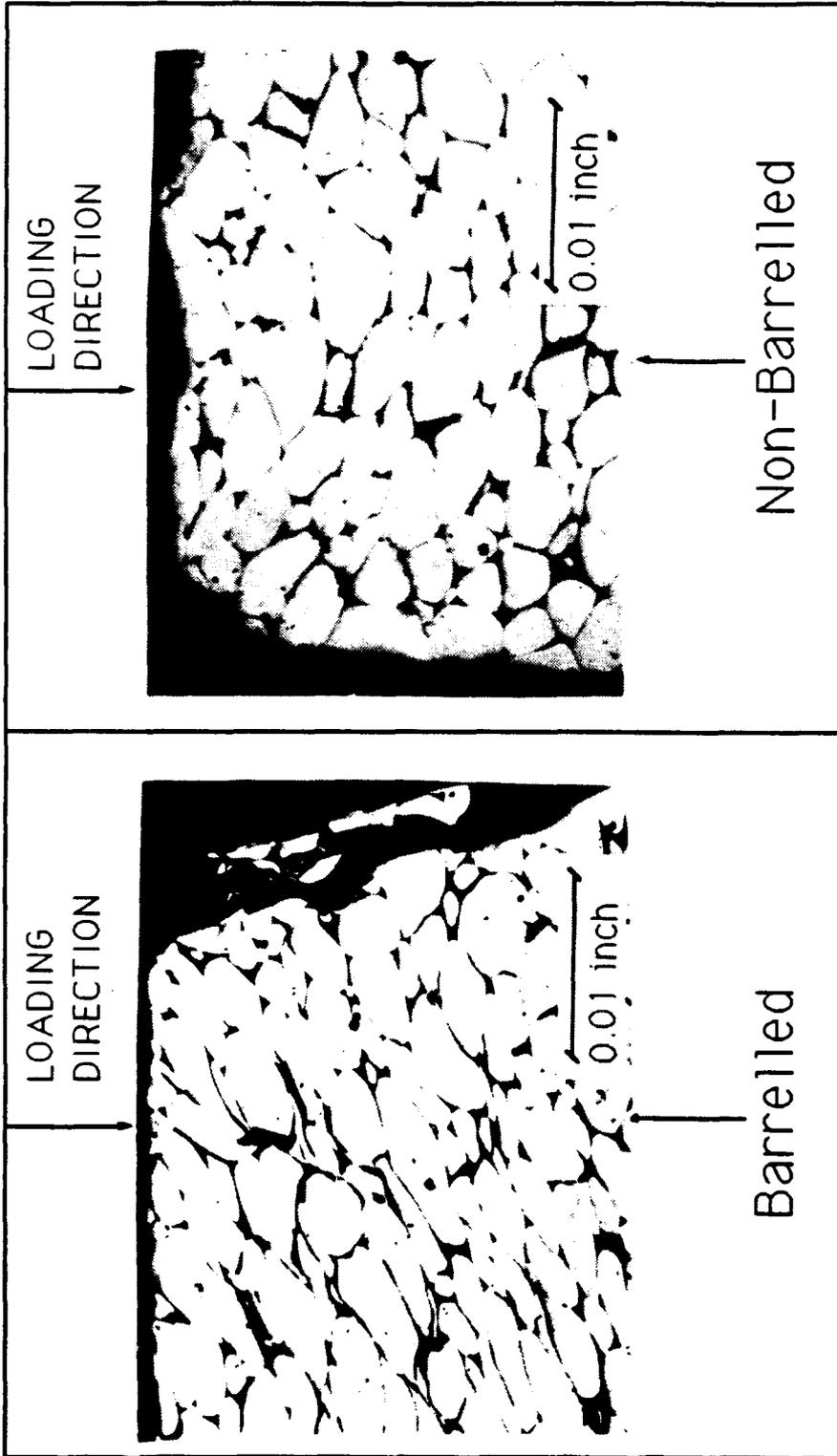


Figure 9. Microphotographs of 97.2% W alloy (Kennametal's W2) comparing barrelled and nonbarrelled specimens, at a magnification of 100X.

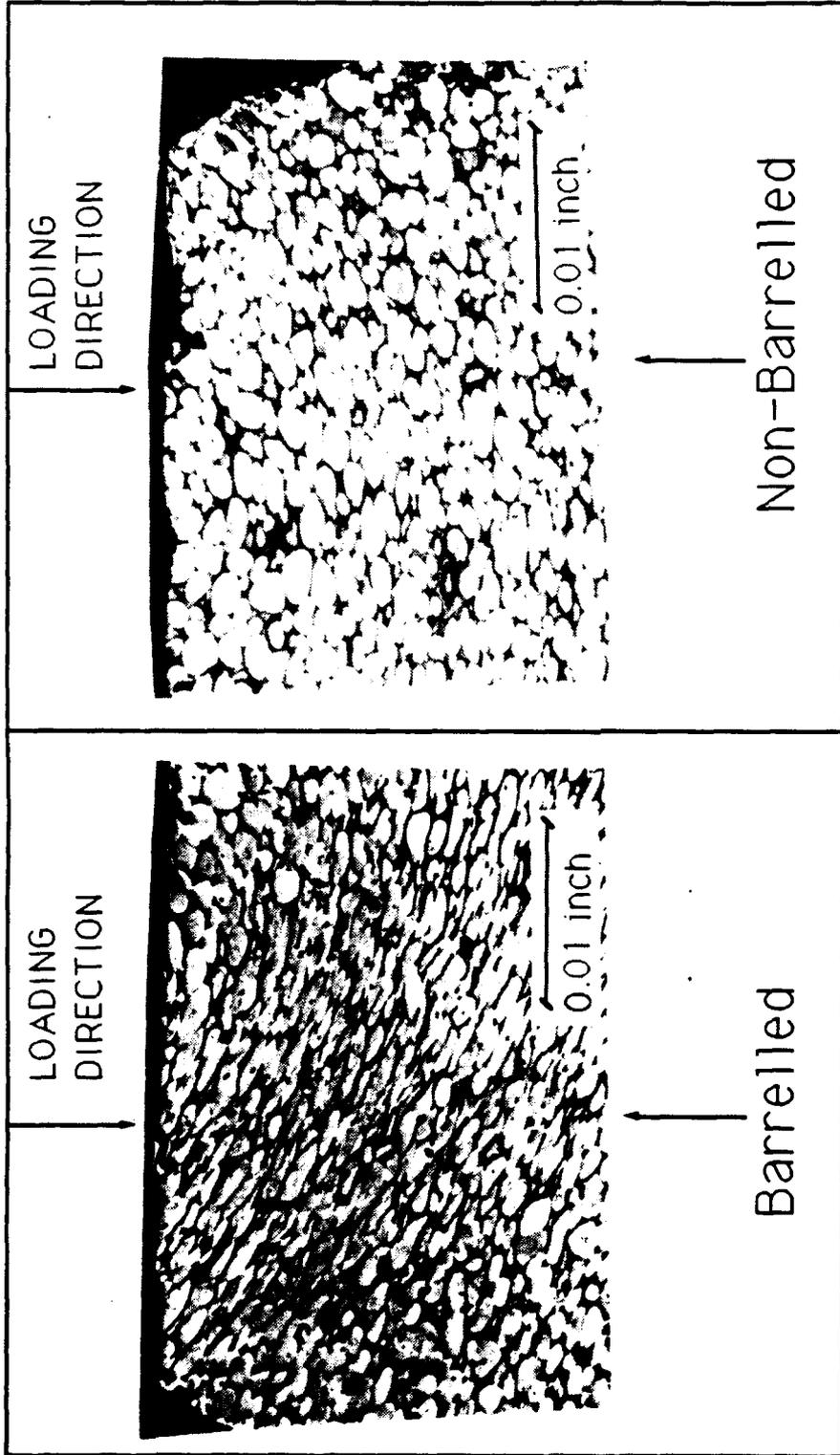


Figure 10. Microphotographs of 93% W alloy (X21) comparing barrelled and nonbarrelled specimens, at a magnification of 100X.

APPENDIX

A-1 Manufacturer's Chemical and Material Properties

Material

The tungsten alloys (W2 and X21) were products of powder metallurgy. The ease with which they can be machined and their large weight-to-volume ratio makes them ideal candidate materials for static and dynamic applications; i.e., penetrators. The chemical composition of W2 and X21 tungsten alloys are given in Table A-1. The nominal mechanical properties of the tungsten alloys acquired from manufacturer's data sheets are displayed in Table A-2.

Table A-1. CHEMICAL COMPOSITION OF W2 AND X21 TUNGSTEN ALLOYS

Material	W (%)	Ni (%)	Fe (%)	Cu (%)	Co (%)
W2	97.2	1.5	0.7	0.5	0.1
X21	93.0	4.9	2.1	---	---

Table A-2. MECHANICAL PROPERTIES OF W2 AND X21 TUNGSTEN ALLOYS PROVIDED BY MANUFACTURER

Property	Material	
	W2	X21
Tensile Strength (MPa)	827.4	920
Modulus of Elasticity (GPa)	358.5	*
Elongation (%)	9	28
Poisson's Ratio	0.27	*
Hardness (Rockwell C)	27 to 32	30
Density (g/cc)	18.5	17.74

*Not available from manufacturer.

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1	NASA - Lewis Research Center, 2100 Brookpark Road, Cleveland, OH 44135-3191
2	Director, U.S. Army Materials Technology Laboratory, Watertown, MA 02172-0001 ATTN: SLCMT-TML
2	Authors

U.S. Army Materials Technology Laboratory
Watertown, Massachusetts 02172-0001
LARGE STRAIN COMPRESSION OF TWO TUNGSTEN
ALLOYS AT VARIOUS STRAIN RATES.
John L. Green and Paul Moy

Technical Report MTL TR 92-66, September 1992, 17 pp-
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Key Words

Tungsten alloys
Strain rate
Compression tests

This report describes the material characterization of two tungsten alloys in terms of their modulus of elasticity, yield stresses, and true stress-true strain curves. These alloys are W2 (Kannametal) with 97.2% tungsten and X21 (Teledyne, Firth, and Sterling) with 93% tungsten. Both alloys were compressed to strains between 40% and 75%, and at strain rates between 0.0001/sec and 3000/sec. The experiments were conducted in the Medium Strain Rate Machine (MSRM) and Split Hopkinson Pressure Bar (SHPB) facilities at the U.S. Army Materials Technology Laboratory (MTL). The effect of strain rate was ascertained for each alloy and a comparison conducted on their stress-strain relationships. Metallographic examinations of the microstructure were conducted on both tungsten alloys to determine if adiabatic shear bands had developed. Zones of shear deformation were observed but were attributed to frictional effects at the ends of specimens. At large deformations, frictional effects cause specimen barreling and a three-dimensional stress state. Annular grooves were machined into the ends of the specimens and, in addition, Teflon™ sheets provided lubrication thereby eliminating frictional effects. Both alloys are strain rate sensitive; however, the W2 alloy is somewhat more sensitive at higher strain-rates. No adiabatic shear bands were observed and shear deformation due to frictional effects was eliminated by using the modified specimen and Teflon™ sheeting.

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