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Yield Properties of Tungsten and Tungsten Heavy Alloys

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ARL-TR-143

June 1993

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REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*

2. REPORT DATE June 1993

3. REPORT TYPE AND DATES COVERED Reprint - Final Report

4. TITLE AND SUBTITLE
Yield Properties of Tungsten and Tungsten
Heavy Alloys

5. FUNDING NUMBERS

6. AUTHOR(S)
Kenneth F. Ryan and Robert J. Dowding

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
U.S. Army Research Laboratory
Watertown, Massachusetts 02172-0001
ATTN: AMSRL-MA-MB

8. PERFORMING ORGANIZATION REPORT NUMBER
ARL-TR-143

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
U.S. Army Research Laboratory
2800 Powder Mill Road
Adelphi, Maryland 20783-1197

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES Presented at the International Tungsten Symposium, Washington, DC, Nov. 16-18, 1992.
Published in the Proceedings of the first International Conference on Tungsten and Tungsten Alloys - 1992.

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

This report describes the progress made in dynamic thermo-mechanical investigations, using the Gleeble® 1500, of the yield properties of tungsten heavy alloys. This study describes properties of tungsten heavy alloy at elevated temperatures and strain rates, that can be useful in the modeling of long rod kinetic energy penetrator behavior.

14. SUBJECT TERMS
Tungsten alloys, Compression, Annealing, Process control, Deformation, Strain rate, Mechanical properties

15. NUMBER OF PAGES 12

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	**18. SECURITY CLASSIFICATION OF THIS PAGE**	**19. SECURITY CLASSIFICATION OF ABSTRACT**	**20. LIMITATION OF ABSTRACT**
Unclassified	Unclassified	Unclassified	UL

NSN 7540-01-280-5500

Standard Form 298 (Rev 2 89)
Prescribed by ANSI Std Z39-18
298-102

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YIELD PROPERTIES OF TUNGSTEN AND TUNGSTEN HEAVY ALLOYS

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Abstract

This report describes the progress made in dynamic thermo-mechanical investigations, using the Gleeble® 1500, of the yield properties of tungsten heavy alloys. This study describes properties of tungsten heavy alloy at elevated temperatures and strain rates, that can be useful in the modeling of long rod kinetic energy penetrator behavior.

Introduction

Tungsten heavy alloys have application as long rod kinetic energy (K.E.) penetrators if some of their properties can be improved. The goal is that they perform as well as those made from depleted uranium (DU). Penetrator applications require the highest level of toughness, strength, hardness, and ductility. Commonly, the most useful heavy alloy compositions are based upon the W-Ni-Fe ternary, with tungsten contents ranging up 97 wt pct. The balance is nickel and iron most often in a ratio of 7:3. Recent work indicates that the toughness of 8:2 nickel:iron ratios is greater than the traditional 7:3 but these have not been ballistically tested on a widespread basis [1]. Ballistic testing at the Materials Directorate of the Army Research Laboratory (formerly the Army Materials Technology Laboratory) has employed the depth of penetration (DOP) test for many tungsten alloys; most predominately those with approximately 90-93 % tungsten, with a matrix composition that contained nickel, iron, and/or cobalt. A full description of the DOP test can be found in Woolsey, et al. [2]. These results revealed that density is the only apparent driver of performance in this test. This work also demonstrated that the mechanical properties have little influence over performance in the DOP test [3]. This work supported the observations of Ekbom, et al., who stated that strength was not a primary factor in penetration of homogenous targets [4].

GTE Sylvania (Towanda, PA) performed an extensive study on the interrelationship between chemical composition, thermo-mechanical processing history, microstructure and ballistics performance of tungsten heavy alloys. Among the significant findings of that program was that the optimum mechanical properties were attained when the nickel:iron ratio of W-Ni-Fe alloy was 8:2, instead of the traditional 7:3 which has historically been thought to be better. The 8:2 ratio had superior mechanical properties and in some cases showed slightly improved ballistic properties. In general though, no strong correlation could be drawn between the mechanical properties and ballistic performance [1].

The problem with all previous efforts to correlate mechanical properties to ballistic properties has been the use of quasistatic testing rather than testing at elevated strain rates. There has been a move lately to change this approach and evaluate the ballistic potential of penetrator alloys with high strain rate test procedures [5-8] largely employing the split Hopkinson bar apparatus, in both compression and torsion. Along with this change has been the realization that to be able to model material response of a penetrator using computer codes requires that the properties of the *relevant* tungsten alloy are needed rather than the properties of pure tungsten.

Previous research by Bose, et al., involved generating data on mechanical property variations with test temperature and strain rate for a common tungsten heavy alloy with a well characterized microstructure and processing history [9]. These results were gathered using tension specimens over a range of temperatures and strain rates. Data of this type and the data to be presented here can be very useful in developing materials models for ballistic interactions.

A microprocessor controlled, dynamic, thermo-mechanical test machine called the Gleeble® 1500, was used to determine the mechanical response of a commercially available 91% tungsten heavy alloy. This type of experimental testing can provide some of the constitutive data necessary for developing modeling and processing simulations. The ultimate objective is to determine the processing/properties/microstructure required to optimize the performance of tungsten heavy alloys for use as kinetic energy penetrators.

Evaluation of the data from elevated temperature deformation experiments depends on the choice of constitutive equations. These equations hopefully are the ones that most accurately express the material's response. It is desirable for such a constitutive model to be based on physical processes that occur within the alloy over wide ranges of temperatures and strain rates, and yet the model must contain measurable parameters from easily performed thermo-mechanical tests [10]. The present approach to describing constitutive relations for metal deformation is based on unifying the microscopic physical processes occurring during deformation [10].

The choice of model significantly affects the simplicity of the test and the number of material constants that must be determined [11]. The Gleeble 1500 is a sophisticated system to help generate the data required to describe the temperature dependent, elevated strain rate, stress-strain behavior of these tungsten heavy alloys. The experimental data can be fitted algebraically into the classic strain rate dependant equations and present a greater understanding of the material's flow behavior in terms of either strain, strain rate or temperature. Often complicated microstructural changes can occur during high temperature deformation processing. These include: strain hardening, strain aging, recovery and recrystallization. Because of this it is very difficult, if not impossible to describe the complete elevated temperature deformation behavior using a single relationship [12].

Background Theory

Many attempts have been made to fit mathematical equations to describe the steady state stress-strain rate material behavior. The simplest, and hence, most common is a power law expression of the form;

$$\sigma = A\epsilon^{m} \qquad \text{equation 1}$$

where constant A is the stress at a strain rate of one obtained at constant strain and temperature, and m is the strain rate sensivity as determined by the slope of a log-log plot of this equation [13]. This power law expression will most often adequately describe the dependance between flow stress and strain rate. A similar relationship can be derived for stress-strain behavior obtained at constant strain rate and temperature. By experimental observation during this study, we've found the expected relationship where increasing the strain rate increases the material's flow stress. The strain rate sensitivity of most metals is usually low at room temperatures, and increases with increasing temperature; especially at temperatures greater than half the melting point [14]. The temperature range investigated here is well below the melting temperature (T_m) of pure tungsten but is much above 0.5 T_m of the multicomponent matrix phase. This can be expected to cause difficulty in interpreting the data of this two-phase composite.

The temperature dependence of the flow stress at constant strain and strain rate can be represented by the relationship known as the Arrhenius equation:

$$\sigma = C \exp(Q/RT) \qquad \text{equation 2}$$

Where Q = activation energy, R = the universal gas constant, T = test temperature (°K) and C = a material dependent constant. A plot of ln σ versus 1/T will yield a straight line with a slope of Q/R. This allows the simple calculation of the activation energy at all temperatures and strain rates and is obtained from the material's flow stress behavior. The magnitude of the activation energy is indicative of the metallurgical processes occurring during deformation, such as, strain aging or recrystallization. Previous hot working studies performed by Tuler provide a perception that thermally activated processes assist deformation and reduce the flow stress at elevated temperatures [14].

Experimental Procedure

Cylindrical specimens 0.245" in diameter and 0.368" long (L/D=1.5) were machined from a 91% tungsten heavy alloy purchased from a commercial source. The ends of these compression specimens were ground flat and parallel within ± 0.0005". Additionally, they were designed to minimize the possibility of buckling when loaded on end. The quasistatic properties and the chemical content of the major constituents of the tungsten heavy alloy chosen for this testing are presented in Table 1.

The Gleeble 1500 test set-up can be seen in Figure 1. The specimen was compressed between two tungsten carbide anvils with graphite as a lubricant to prevent excessive barreling of the specimen during testing. The temperature range for the compression testing was 500° to 1000° C and the heating was accomplished be electrical resistance and monitored by a thermocouple. The average strain rates were in the range of 10^{-2} to 10^{-1} sec^{-1} and the total compressive strain applied was 20%. These strain rates bridge the gap from quasistatic to dynamic. Figure 2 graphically describes the test procedure used for this work. Note that the 1200° C anneal prior to compression was required since the supplied material was previously swaged. The cooling rates to each of the test temperatures varies because free cooling to those temperatures was used and no attempt was made to control the rate.

TABLE 1
ROOM TEMPERATURE, QUASI-STATIC MECHANICAL PROPERTIES
AND
CHEMICAL ANALYSIS OF TUNGSTEN HEAVY ALLOY

0.2% YIELD STRENGTH (MPa)	UTS (MPa)	REDUCTION IN AREA (%)	ELONGATION (%)
1167	1178	16.8	11.9
TUNGSTEN (wt%)	NICKEL (wt%)	IRON (wt%)	COBALT (wt%)
90.73	4.55	1.97	2.75

Results and Discussion

Figure 3 shows the thermo-mechanical response of the 91% tungsten heavy alloy at strain rates in the range of 1.6 to 1.8 x 10^{-2} sec^{-1}. The figure shows the expected result that the yield strength and flow strength decrease with increasing test temperature. Figure 4 displays the strength at a total strain of 0.002 versus test temperature for each of the strain rates used. Also plotted is data for room temperature compression of the as-annealed specimens. The 0.002 strength data was obtained directly from the data acquisitions and not graphically from the plots shown in Figure 3. This results in a more accurate interpretation of the yield data.

Figures 5 describes the temperature dependence of flow stress of the heavy alloy at the two temperature extremes and the two average strain rates examined in this work. This figure shows the expected result that yield and flow stress increases with increasing strain rate.

Figure 6 summarizes the data obtained in terms of equation 1 where the slope of the curve represents the strain rate sensivity (m). The strain rate sensivity of metals increases with increasing temperature and is an indicator of changes in deformation behavior. In a composite material such as this heavy alloy, the elevated deformation behavior is complicated by the differing properties of the two phases. Whereas the matrix has a melting point of approximately 1453° C the tungsten particles melt at over 3300° C. The strain rate sensivity is said to increase significantly over 0.5 T_m. The strain rate sensivity as determined here is somewhat constant up to 800° C but apparently increases at 1000° C. This may be because the temperature exceeds 0.5 T_m of the matrix by a significant degree. Certainly more data must be obtained to determine if this observation is correct.

Figure 7 is an Arrhenius plot based on equation 2. The slope of the line is the activation energy (Q) of the deformation event at the strain rates given. It is apparent from an examination of this data that there are two deformation regimes; one below 800° C and one above. The activation energies below 800° C were calculated to be 4.33 and 5.02 kJ/mole for the strain rates $1.75x10^{-2}$ and $1.84x10^{-1}$ sec^{-1} respectively. Above 800° C the activation energies were found to be 27.44 and 34.03 kJ/mole respectively. Since the strain rates used here are relatively close, only one order of magnitude different, the activation energies are nearly identical.

Summary and Conclusions

Cylindrical compression tests were conducted on a 91% tungsten heavy alloy in the temperature range 500-1000° C to a total strain of 20% using two average strain rates of $1.84x10^{-2}$ and $1.75x10^{-1}$ sec^{-1}. The alloy exhibited the expected strain and strain rate hardening, as well as, thermal softening. The strain rate sensivity at 1000° C was found to be slightly higher than at lower temperatures but this observation needs to be verified with additional data. Very little variation in the activation energy was noted for the two strain rates examined. This was attributed to the small difference between them. More testing is required to verify data obtained and to extend to envelope of information.

References

1. J.R. Spencer and J.A. Mullendore, "Relationship Between Composition, Structure, Properties, Thermo-Mechanical Processing and Ballistic Performance of Tungsten Heavy Alloys", U.S. Army materials Technology Laboratory, Watertown, MA 02172-0001, MTL TR 91-44, November 1991.
2. P. Woolsey, D. Kokidko and S.A. Mariano, "Alternative Test Methodology for Ballistic Performance Ranking of Armor Ceramics", U.S. Army Materials Technology Laboratory, Watertown, MA 02172-0001, MTL TR 89-43, April 1989.
3. R.J. Dowding, K.J. Tauer, P. Woolsey and F.S. Hodi, "The Metallurgical and Ballistic Characterization of Quarter-Scale Tungsten Alloy Penetrators", U.S. Army materials Technology Laboratory, Watertown, MA 02172-0001, MTL TR 90-31, May 1990.
4. L. Ekbom, S.Bogegård, L. Holmberg and L. Westerling, Proceedings 9th International Symposium on Ballistics, pp 2-447 to 2-456, 1986.
5. D. Chaiat, Proceedings of 1986 P/M in Defense Technology Seminar, MPIF, Princeton, NJ, pp 1-13, 1986.
6. A. Bose, S.C. Yang and R.M. German, Proceedings of 1991 P/M Conference and Exhibition, Vol. 6, Chicago, MPIF, Princeton, NJ, 1991, pp 425-437.
7. A. Bose, H. Couque and J. Lankford, Jr., Proceedings of 1992 P/M World Congress, San Francisco, MPIF, Princeton, NJ, in press.
8. T. Weerasooriya, P.A. Beaulieu and R. Swanson, these proceedings.
9. A. Bose, D. Sims and R.M. German, Metallurgical Transactions A, vol 19A, March 1988, pp 487-494.

10. A.K. Ghosh, Acta Metallurgica, vol 28, Pergamon Press, 1980, pp 1443-1465.
11. G.A. Henshall and A.K. Miller, Acta Metallurgica, vol 37, Pergamon Press, 1989, pp 2693-2704.
12. K.P. Rao and E.B. Hawbolt, Transactions of the ASME, Journal of Engineering Materials and Technology, vol 114, 1992, pp 116-123.
13. G.E. Dieter, Mechanical Metallurgy, 2nd Ed., McGraw-Hill, Inc., 1976.
14. J.T. Beals, C. Demetry and F.R. Tuler, "High Temperature Deformation of Silicon Carbide-Reinforced 6061 Aluminum Metal Matrix Composites", Worcester Polytechnic Institute, Worcester, MA, Proj. No. FRT-8782, 1988.

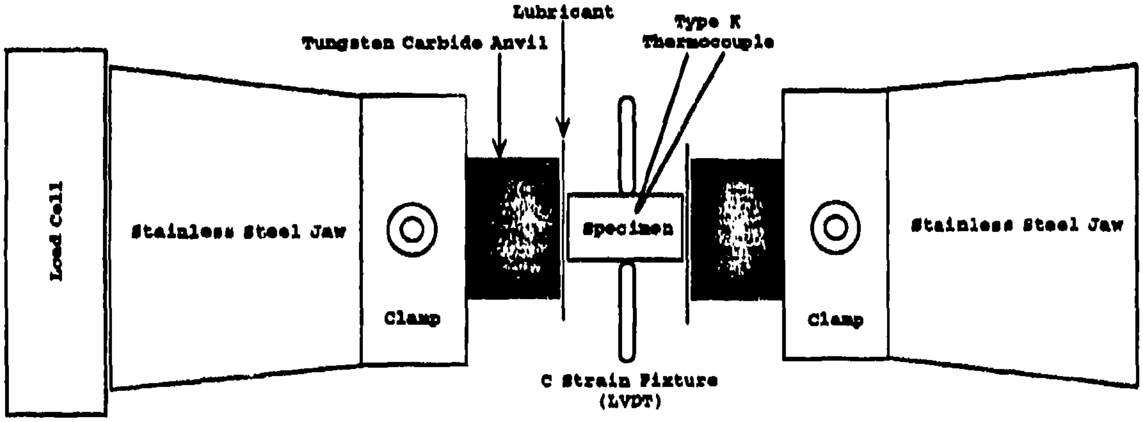


Figure 1 Schematic Drawing of the Gleeble 1500 Compression Testing Equipment

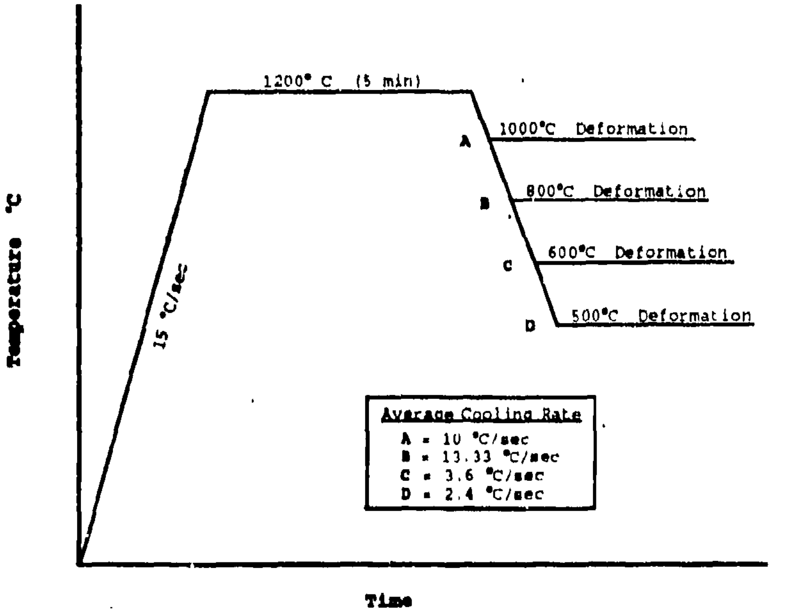


Figure 2 Thermal Profiles for Specimens Prior to Deformation, Includes 1200°C Stress Relief and Free Cool, in Vacuum to the Test Temperature. Heating and Cooling Rates are Shown.

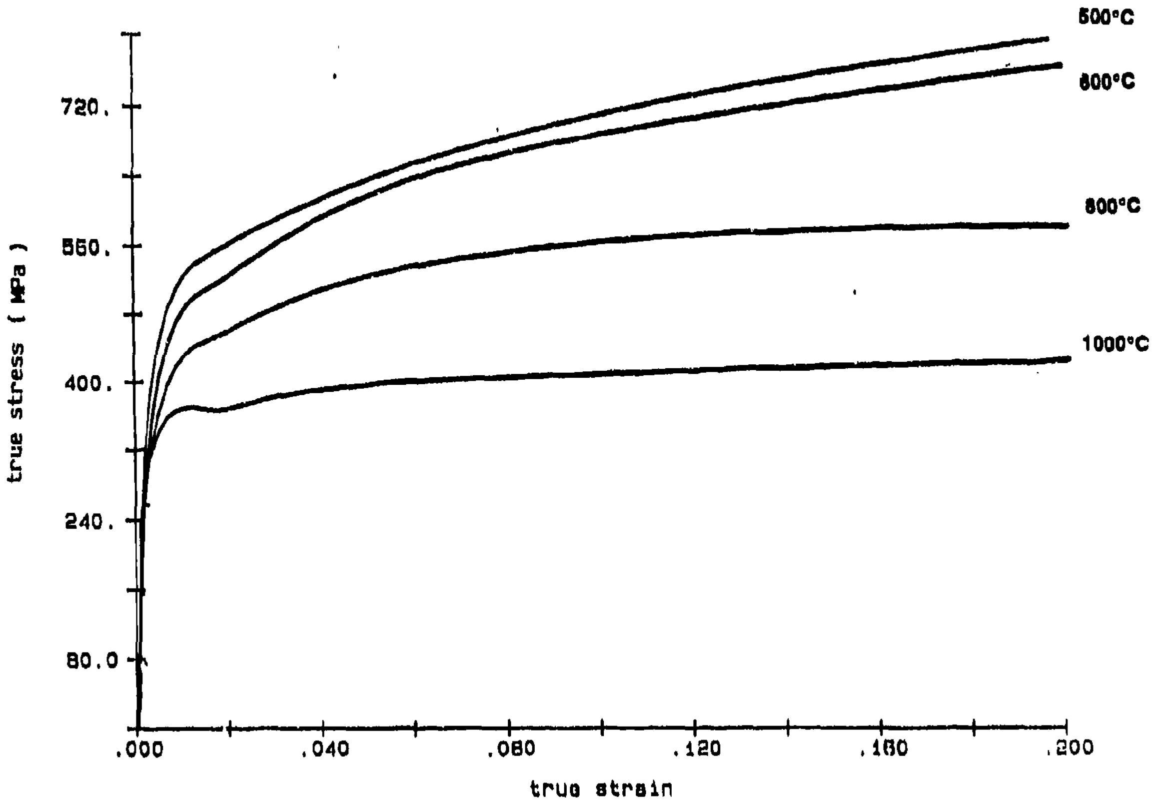


Figure 3 Thermo-mechanical Response at a Constant Strain Rate in the Range (1.6 - 1.8 x 10^{-2} sec^{-1})

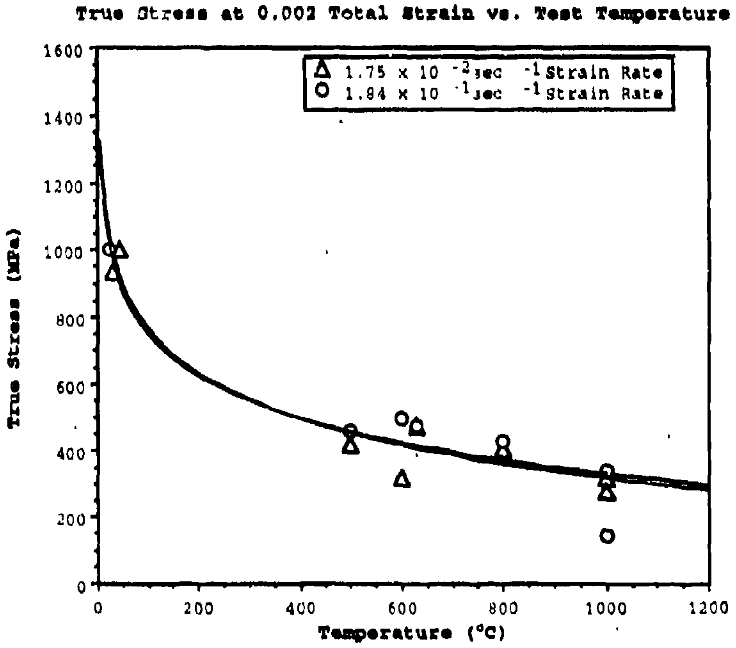


Figure 4 True Stress at 0.002 Total Strain at Two Different Average Strain Rates

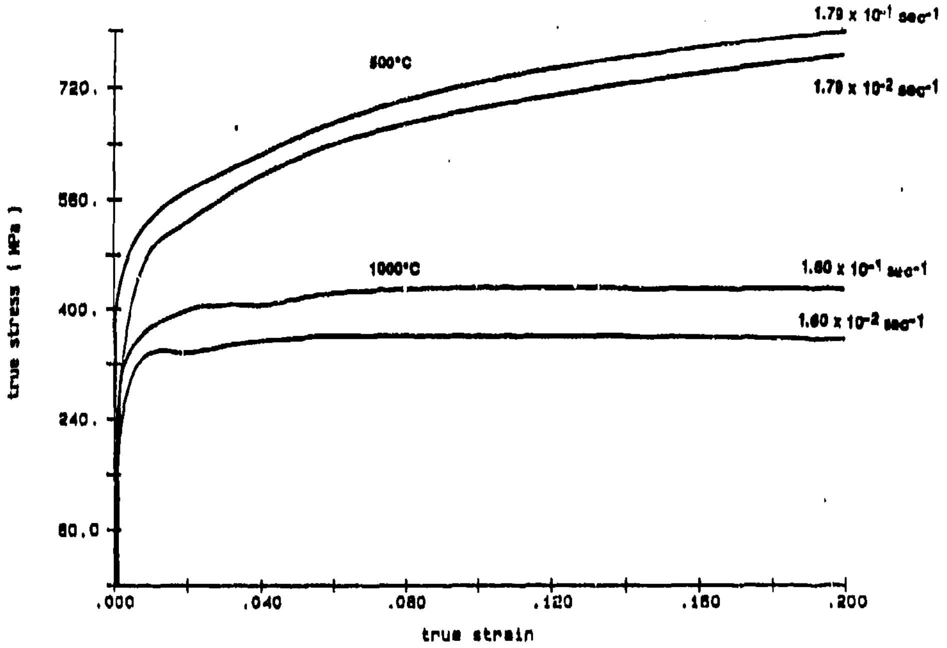


Figure 5 Temperature Dependence at 500°C and 1000°C

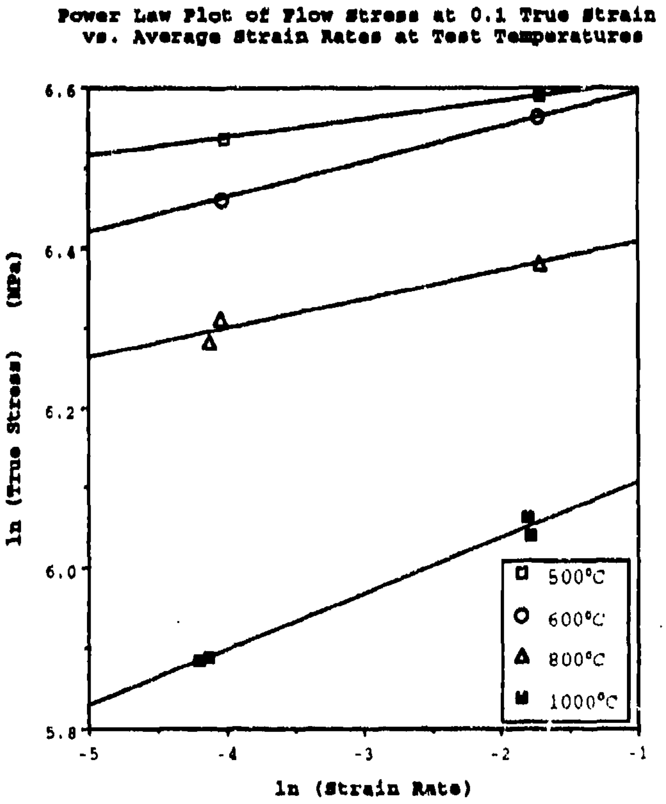
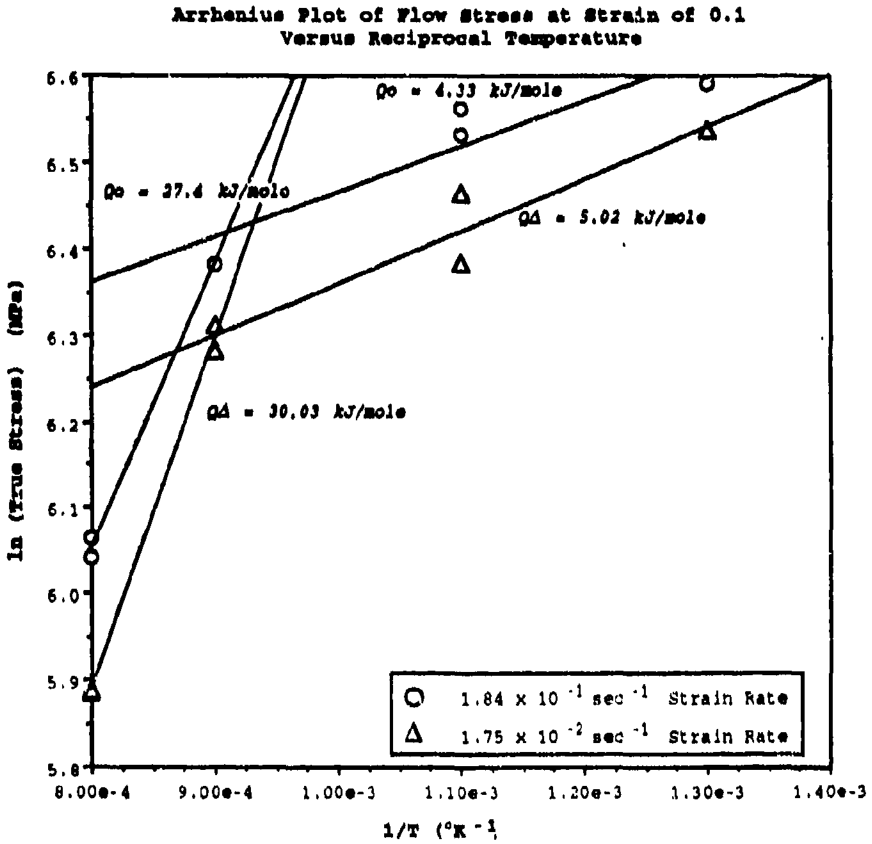

Power Law Plot of Flow Stress at 0.1 True Strain vs. Average Strain Rates at Test Temperatures

Figure 6 Power Law Plot of Flow Stress Versus Average Strain Rates at Various Test Temperatures



Arrhenius Plot of Flow Stress at Strain of 0.1
Versus Reciprocal Temperature

Figure 7 Arrhenius Plot of True Stress Versus Reciprocal Temperature

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