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Yield strength of molybdenum, tantalum and tungsten at high strain rates and very high temperatures ☆

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ABSTRACT

Recently reported results of the high strain rate, high temperature measurements of the yield strength of tantalum and tungsten have been analyzed along with new experimental results on the yield strength of molybdenum. Thin wires are subjected to high stress by passing a short, fast, high current pulse through a thin wire; the amplitude of the current governs the stress and the repetition rate of the pulses determines the temperature of the wire. The highest temperatures reached in the experiments were 2100 °C (for molybdenum), 2250 °C (for tantalum) and 2450 °C (for tungsten). The strain-rates in the tests were in the range from 500 to 1500 s^{-1}. The parameters for the constitutive equation developed by Zerilli and Armstrong have been determined from the experimental data and the results have been compared with the data obtained at lower temperatures. An exceptionally good fit is obtained for the deformation of tungsten.

1. Introduction

Tungsten, tantalum, molybdenum and their alloys are the prefered candidates for many high strain rate applications, for example kinetic energy penetrators [1,2]. Tungsten has been used for many decades in high temperature applications, as well as molybdenum which finds most of its applications at elevated temperatures. Even so, there is a lack of experimental data on the thermomechanical response of these refractory metals to high strain rate effects at temperatures higher than 1000 °C.

The behavior of materials under these conditions is of great interest from phenomenological point of view, for example for testing the consistency of the different constitutive models. In addition to this, the materials used in the target systems in the next generation of high power particle accelerators will be more and more frequently exposed to the combination of high stresses, high strain rates and high temperatures. In order to estimate the lifetime of the target and target system components in this environment, the candidate materials must be tested under extreme conditions.

As part of the UK programme of high power target developments for a Neutrino Factory [3] a new dynamic method for thermomechanical characterization of the candidate target materials has been developed [4,5]. The method is based on heating and stress applied to a thin wire (less than 1 mm diameter) of the candidate material by a fast (~1 μs long), high current (up to 9200 A) pulse. This paper is a continuation of the study presented in [5] where the yield strength of tungsten and tantalum has been measured at strain rates from 500 to 1500 s^{-1} and at temperatures much higher than previously recorded in the literature.

The same method has been applied in experiments with molybdenum wires and hot forged tungsten bars. The results obtained are presented in this paper for the very first time. In addition, this paper is focused on the analysis of all these new yield strength data, constitutive modelling and comparison with previous results for molybdenum, tantalum and tungsten.

The rest of the paper is organized as follows. The description of the experimental procedure and results are given in Section 2. Section 3 describes the constitutive modelling procedure with special attention paid to the Zerilli and Armstrong model [6]. The results are discussed in Section 4, followed by the summary in Section 5.

2. Experimental procedure and results

A thin wire is necessary to allow the current to diffuse into the center of the wire in a sufficiently short time to generate the required thermal stress. The tungsten, tantalum and molybdenum wires with diameters from 0.5 mm to 0.8 mm have been made by standard powder metallurgy methods – pressing, sintering, forging and finally drawing. The tungsten wires have been additionally stress relieved at about 400 °C. The purity of the wires

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Table 1
Typical content of impurities (in ppm) in tungsten, tantalum and molybdenum samples used in this experiment.

Impurity	Tungsten wire	Tungsten bar	Tantalum wire	Molybdenum wire
Al	10		5	20
Fe	20	20	30	60
K	50			30
Mo	40	150	100	
Na	5		10	10
Ni	<10	<20	3	20
Si	45	<50	10	50
N	6	10		
O	15	30		
C		30		15
W			100	

used in the tests was at least 99.9 %. Table 1 shows the typical content of impurities in the samples as given by the manufacturer.[1]

To determine the yield strength the pulse amplitude of the current in the wire was increased in steps at a fixed temperature. The current was kept constant for 3–5 min before taking the next increase. This was continued until the wire was observed to start bending or kinking. The surface motion of the test wire during the pulsing is measured by a laser Doppler vibrometer (LDV) from Polytec [7]. The radial surface velocity measured by the LDV (see, for example, Fig. 1), is used to extract the strain rate during the test. The optical sensor head of the LDV includes an integrated fast camera that is used to visually monitor the strain of the wire. In addition, it was noticed that the LDV radial velocity signal would become very noisy as one approached the first signs of plastic deformation, eventually resulting in the loss of any coherent vibration signal. This monitoring and the change of the quality of the LDV signal were the main indicators that the wire is near or at the yield point.

The bent wire was then replaced with a new, straight sample and the experiment was repeated at a new temperature and current. In some cases, the procedure was changed so the current was kept constant and the temperature was changed by adjusting the pulse repetition rate. In order to estimate the systematic uncertainties, at some temperatures there were several tests and it was found that the results were repeatable to within ±5% of the current. An optical pyrometer was used to measure the temperature of the wire at the same point measured by the vibrometer.

The stress in the wire is not directly measured, but it is proportional to the square of the current and can be modelled by using modern finite element codes. The first step is to measure the current pulse in the wire, then to calculate the current density as a function of time and radius using the solution to the diffusion equation [8]. Knowing the current density, the temperature rise is calculated and finally the finite element code LS-DYNA [9] is used to calculate the equivalent (von Mises) stress as a function of time and radius (more details can be found in [4,5,10]). As the stress in the wire is a result of calculation it is important to benchmark the results obtained. Fig. 1 shows the comparison between measured radial surface velocity of the tungsten wire at different temperatures and the LS-DYNA results [5]. The agreement between experiment and simulation is very good and this can be taken as a proof that the corresponding calculated stresses are correct.

Fig. 2 shows the stress at which the molybdenum, tantalum and tungsten wires reached the yield point as a function of temperature. The lower edge of the wide bands indicates the stress at which the wire still appeared undeformed and the upper edge the stress at which the wire started to bend. For tantalum, bands are shown for wires of 0.5 and 0.8 mm diameter. In all the tests, the current was increased in the same, fixed steps. As the stress is inversely proportional to the square of the diameter, the band for the 0.5 mm diameter tantalum wire in Fig. 2 is much wider than for the 0.8 mm diameter wire. In the case of molybdenum and tungsten, 0.5 mm diameter wires have been tested. The highest temperature reached in the experiment was 2100 °C (molybdenum), 2250 °C (tantalum) and 2450 °C (tungsten). On the low side, it was not possible to go below 1150 °C (tantalum), 1270 °C (molybdenumum) and 1450 °C (tungsten) as the minimum temperature is limited by maximum available current.

The peak strain rate is determined by dividing the measured peak radial velocity (see Fig. 1) by the wire radius. The peak strain rates for the measurements of both tantalum and tungsten cover the range (500–1500) s^{-1}. The characteristic values of the strain rate are indicated at various points in Fig. 2. In this experiment the strain rates decrease at high temperatures. The strain of the wire during the pulsing was monitored by a fast camera. These observations were compared to the change in the quality of the LDV signal and it was found that the strain at the yield point was usually between 2% and 4%. Those values have been used also in the constitutive modelling (see Section 3).

Once a wire has begun to distort the stress in the wire increases due to the curvature of the wire. Also accompanying the bending, there is usually stretching and thinning of the wire at the hottest point, so the stress and temperature of the wire increases locally. This all happens within a few pulses and is soon followed by severe bending and/or breaking, so that it is difficult to measure the temperature, diameter and to calculate the true stress in the wire as the plastic strain increases. So, in this experiment it was not possible to measure the 'complete' stress–strain curve but only the yield point.

3. Constitutive modelling

Zerilli and Armstrong [6] proposed the following constitutive (Z&A) equation for the flow stress in body centered cubic (bcc) metals as a function of temperature T, strain ϵ and strain rate $\dot{\epsilon}$:

$$\sigma = C_1 e^{(-C_2 T + C_3 T \ln\dot{\epsilon})} + C_4 + C_5 \epsilon^n + k d^{-1/2}. \quad (1)$$

C_1 to C_5, n and k are material parameters, while d is the grain size. If the precise information about grain size is not available (as in our case), the usual procedure [2,11–13] is to incorporate the grain size term into the C_4 parameter because both are independent of temperature, strain and strain-rate:

$$\sigma = C_1 e^{(-C_2 T + C_3 T \ln\dot{\epsilon})} + C_4 + C_5 \epsilon^n. \quad (2)$$

The first term in this equation combines effects of 'thermal softening' (reduction of yield strength with increasing temperature) and 'strain-rate hardening' (rise of yield strength with increasing strain-rate). This term does not depend on strain. The parameters C_5 and n describe the strain hardening changes. In our case, C_4 and C_5 terms are practically constants (see the previous section) but they are left to vary during the fitting procedure.

The CERN computer package for function minimization MINUIT [14] was used to vary the parameters C_1 to C_5 and n and to minimize the sum of the squares of the deviations (χ^2) between the values obtained from Z&A equation and experimental (fitting) points. The stress value, for each measured set of (T, ϵ, $\dot{\epsilon}$), was chosen to lie in the middle between the corresponding upper and lower stress values (see Fig. 2). The weighted least square fit was used, where the weight of the fitting point, i, is $w_i = 1/\sigma_i^2$, σ_i being the half of the difference between upper and lower edge stress values at particular temperatures.

[1] Goodfellow Cambridge Ltd, http://www.goodfellow.com/

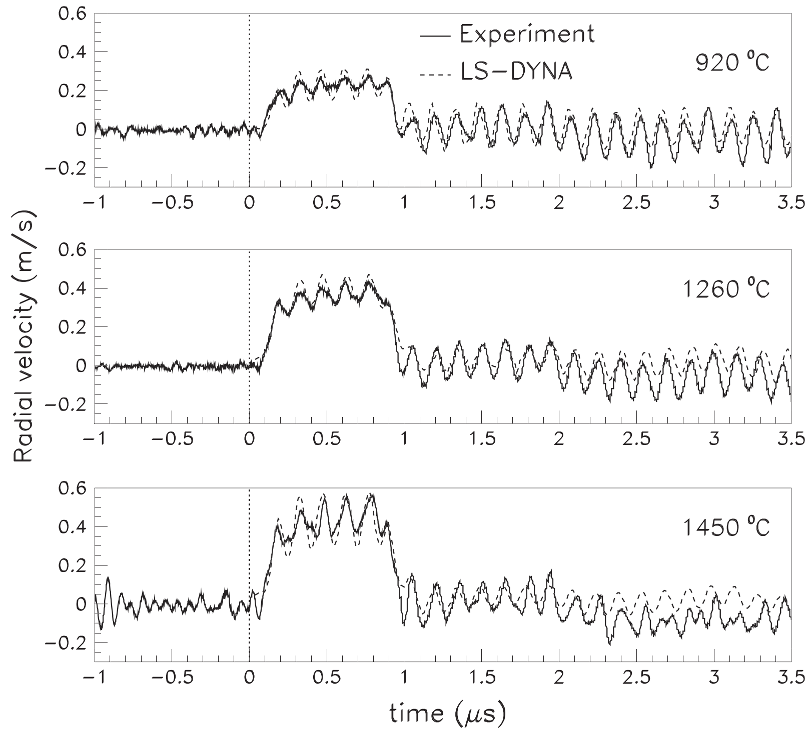

Fig. 1. The measured and calculated radial velocity of a 0.5 mm diameter tungsten wire at peak temperatures of 920, 1260 and 1450 °C [5].

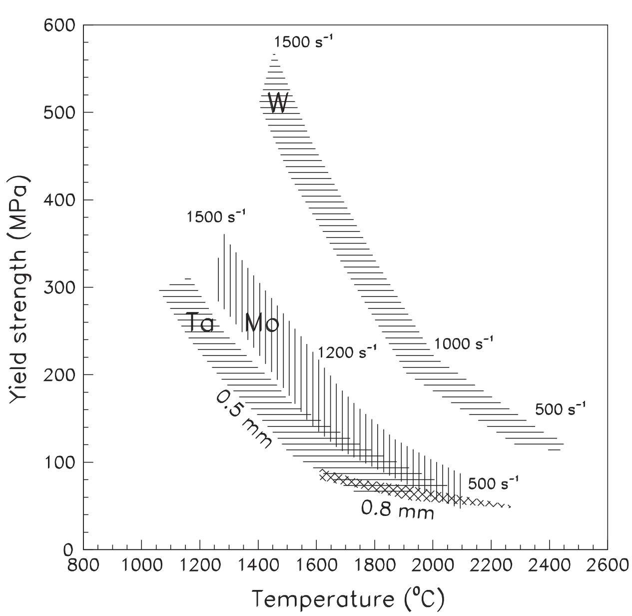

Fig. 2. The yield strength versus peak temperature for tantalum wires of 0.5 and 0.8 mm diameter [5], for tungsten wires of 0.5 mm diameter [5] and for molybdenum wires of 0.5 mm diameter. The upper edge of the bands indicates the stress at which the wire started to bend and the lower edge indicates the stress where the wire was not deformed. The characteristic strain rate values are also shown.

Fig. 3 shows the best fit for the molybdenum data. The best fit of the tantalum data is shown in Fig. 4. One can note that the 0.5 and 0.8 mm data are combined into one set for fitting purposes. Due to the weighted fitting method the fitted curve has a characteristic shape in the region where the results overlap each other. Fig. 5 shows the best fit for the tungsten data. In all three cases the normalized χ^2 value is close to 1.

The corresponding optimized parameters values for molybdenum, tantalum and tungsten are presented in Table 2. One can see that the values of the C_2 and C_3 parameters for all three bcc metals are very similar. This leads to the conclusion that the yield strength dependance on temperature and strain-rate (the slope of the curve) is very similar for these refractory metals at very high temperatures and strain rates at around 1000 s^{-1}.

Finally, using an identical fitting procedure the experimental data was fitted with Johnson–Cook model [15], but this model was found to be inadequate for describing our experimental data. This is in agreement with previous conclusions that the Z&A model is much better equipped to capture strain-rate dependence and thermal softening behavior of bcc metals [2,13].

4. Discussion

4.1. Molybdenum

Table 3 shows the values of the parameters of the Z&A equation obtained in this work and previous experiments with molybdenum samples.

Bourne et al. have listed parameters of Zerilli–Armstrong model for different materials in [16]. Parameters values for molybdenum are based on measurements of Campbell and Briggs [17] and Chen et al. [18]. Campbell and Briggs have used sintered, vacuum annealed molybdenum for moderately high strain-rate (up to 100 s^{-1}) tests at temperatures up to 327 °C. Chen, Maudlin and Gray have measured the stress–strain curve of the commercially pure molybdenum in the strain-rate range of (0.001–4500) s^{-1} and at temperatures ranging from −196 to 600 °C. The corresponding set of molybdenum parameters is denoted as 'BCC' in Table 3 (and Fig. 6 – see below).

Chen et al. [19] have fitted the results of their own experiment where commercially pure molybdenum cylindrical samples of 8 mm diameter and 12 mm height were tested in the strain-rate range of (1–50) s^{-1} and at temperatures ranging from 1100 to 1400 °C. The set of Z&A parameters that corresponds to these experimental results [19] are shown in Table 3 (denoted as 'CYHWQ').

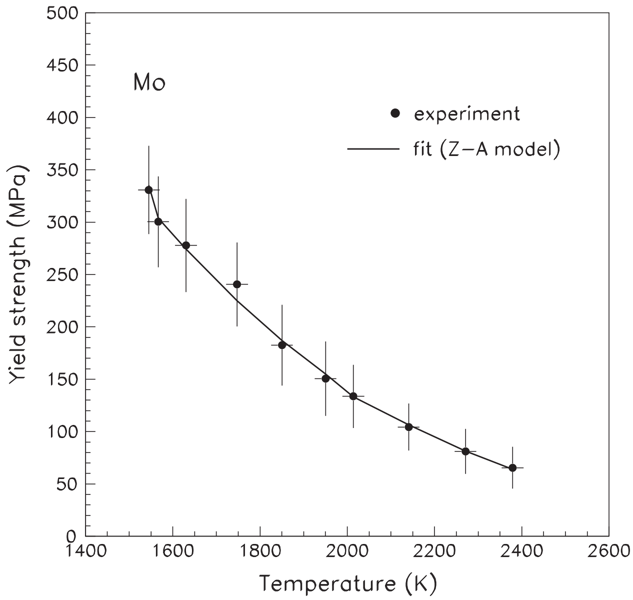

Fig. 3. Experimental data on molybdenum yield strength and the best fit based on Z&A model (parameters values are shown in Table 2).

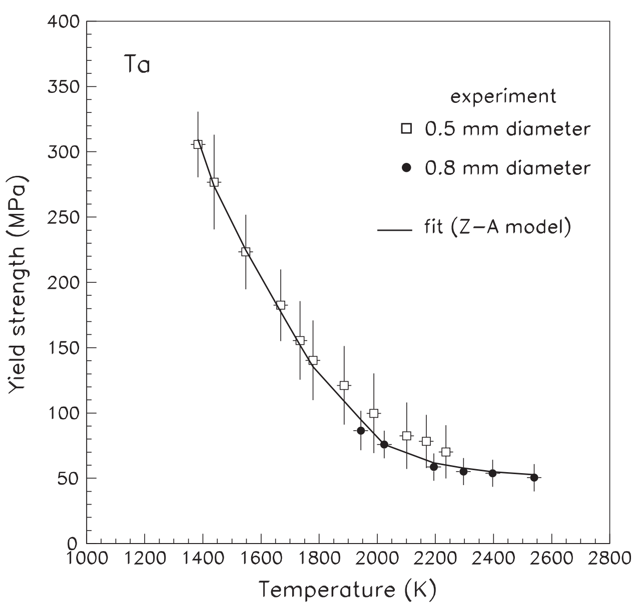

Fig. 4. Experimental data on tantalum yield strength and the best fit based on Z&A model (parameters values are shown in Table 2).

The ‘BCC’ set of parameters describes the thermomechanical properties of molybdenum at temperatures well below the temperature region explored in this work but for similar strain rates.

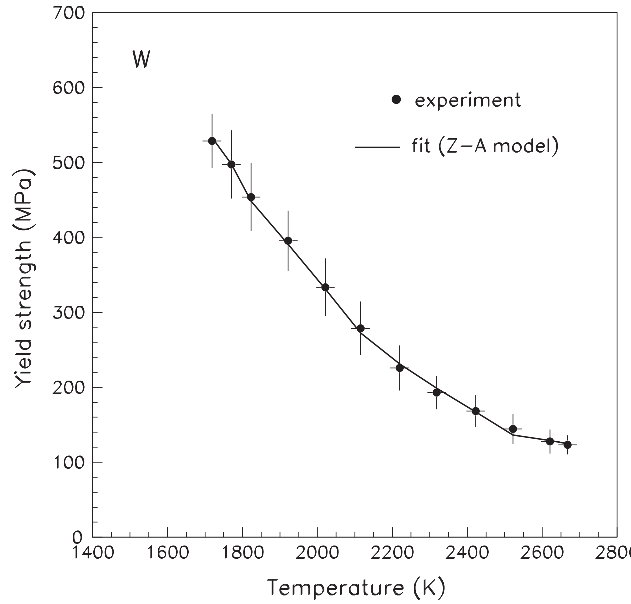

Fig. 5. Experimental data on tungsten yield strength and the best fit based on Z&A model (parameters values are shown in Table 2).

On the other hand, the ‘CYHWQ’ set of parameters covers the temperature region which partialy overlaps the temperatures in our tests but at much lower strain rates values. In an attempt to compare our new results with these, the molybdenum yield strength was calculated using the Z&A constitutive equation for the strain rate of 1000 s^{-1} and strain of 3% (characteristic values in our experiment) and plotted in Fig. 6 as a function of temperature. All parameter sets from Table 3 have been used and the results based on parameters from [16,19] are extrapolated to cover the temperature and strain rate ranges of our experiment. Visual inspection of Fig. 6 reveals that the extrapolated results of the previous experiments differ significantly between themselves (up to a factor of 5) in the temperature region explored in our experiment while our data lie between these two sets.

4.2. Tantalum

Table 4 shows the values of the parameters of the Z&A equation obtained in this work and previous experiments with tantalum samples.

One of the first applications of the Z&A model was in the analysis [12] when Zerilli and Armstrong fitted Hoge and Mukherjee experimental data for tantalum [20]. Hoge and Mukherjee have tested 99% pure, fully recrystallized, tantalum in the strain-rate range of (0.00001–20,000) s^{-1} and at temperatures ranging from −249 to 527 °C. The corresponding set of obtained parameters is denoted as ‘ZA-HM’ in Table 4 (and Fig. 7 – see below).

Chen and Grey have fitted the same experimental results [20] by optimizing the fit for the entire range of data (parameter set

Table 2
Our results for Z&A model parameters for tungsten, tantalum and molybdenum.

Parameter	Tungsten (W)	Tantalum (Ta)	Molybdenum (Mo)
C_1 (MPa)	4711 ± 261	4166 ± 354	2259 ± 149
C_2 (K^{-1})	$(5.97 \pm 0.28) \times 10^{-3}$	$(7.89 \pm 0.41) \times 10^{-3}$	$(5.01 \pm 0.05) \times 10^{-3}$
C_3 (K^{-1})	$(6.24 \pm 0.42) \times 10^{-4}$	$(8.04 \pm 0.38) \times 10^{-4}$	$(5.05 \pm 0.07) \times 10^{-4}$
C_4 (MPa)	94 ± 8	7.5 ± 0.9	22 ± 5
C_5 (MPa)	133 ± 20	381 ± 40	158 ± 42
n	0.51 ± 0.07	0.56 ± 0.08	0.59 ± 0.10

Table 3
Comparison between this work and previous results [16,19] on Z&A model parameters for molybdenum.

Parameter	BCC [16]	CYHWQ [19]	This work
C_1 (MPa)	937	1030	2259
C_2 (K^{-1})	3.6×10^{-3}	7.45×10^{-4}	5.01×10^{-3}
C_3 (K^{-1})	3.07×10^{-4}	2.94×10^{-5}	5.05×10^{-4}
C_4 (MPa)	22.7	−16.515	22
C_5 (MPa)	647	−48.31	158
n	0.0401	−0.4912	0.59

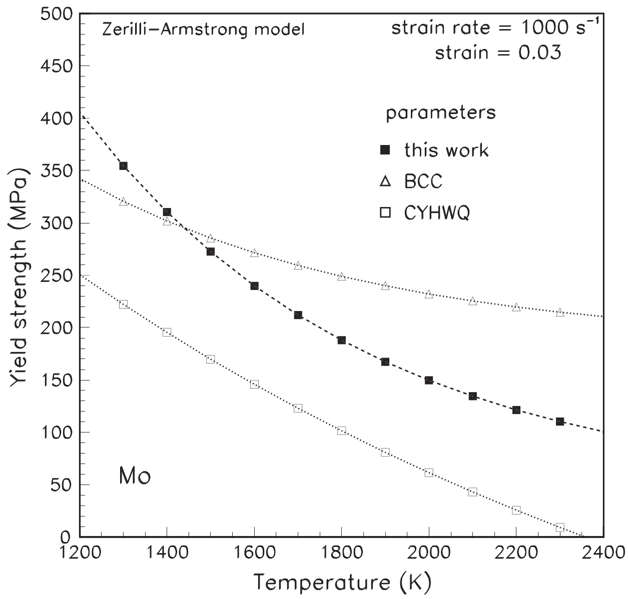

Fig. 6. Molybdenum yield strength, calculated using the Z&A constitutive equation, as a function of temperature for the strain rate of 1000 s^{-1} and strain of 3%. Parameterizations 'BCC' [16] and 'CYHWQ' [19] are extrapolated to cover the temperature and strain rate ranges explored in this work.

'CG-HM' in Table 4). They have also performed their own experiment described in the same paper [11] where commercially pure tantalum was tested in the strain-rate range of (1500–5000) s^{-1} and at temperatures up to 1000 °C. One of the conclusions of the experiment was that the new data are very different from the Hoge and Mukherjee data. The set of Z&A parameters that corresponds to Chen and Grey experimetal results [11] are shown in Table 4 (denoted as 'CG').

In another Chen and Grey experiment [13] commercially pure, triple electron beam melted, vacuum annealed tantalum plates were tested in the strain-rate range of (0.001–4000) s^{-1} and at temperatures ranging from −196 to 1000 °C. Tantalum samples in those tests were prepared by melting large ingots, then forging them into billets which were then annealed and cut prior to cross rolling. Finally, the plates were straight rolled in the final finishing passes. The fitting of corresponding experimental data resulted in a set of Z&A parameters denoted as 'CG-AP' in Table 4.

Table 4
Comparison between this work and previous results [11–13] on Z&A model parameters for tantalum.

Parameter	ZA-HM [12]	CG-HM [11]	CG [11]	CG-AP [13]	This work
C_1 (MPa)	1125	1200	975	1750	4166
C_2 (K^{-1})	5.35×10^{-3}	6.0×10^{-3}	4.5×10^{-3}	9.75×10^{-3}	7.89×10^{-3}
C_3 (K^{-1})	3.27×10^{-4}	3.875×10^{-4}	2.75×10^{-4}	6.75×10^{-4}	8.04×10^{-4}
C_4 (MPa)	30	25	40	140	7.5
C_5 (MPa)	310	310	525	650	381
n	0.44	0.44	0.5	0.65	0.56

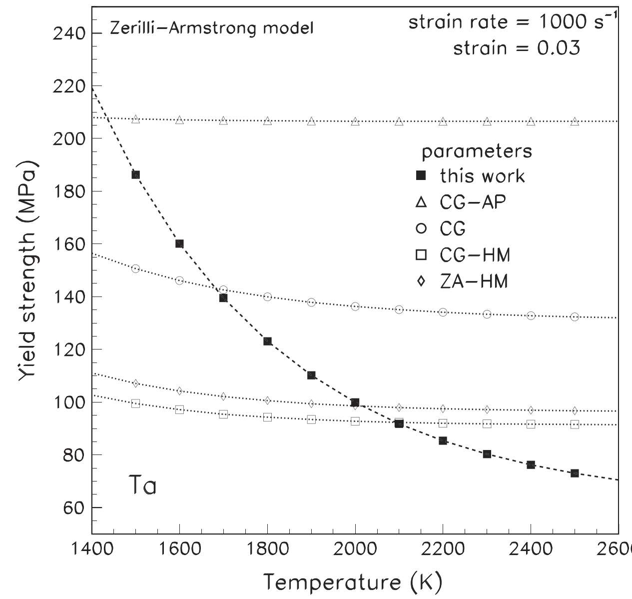

Fig. 7. Tantalum yield strength, calculated using the Z&A constitutive equation, as a function of temperature for the strain rate of 1000 s^{-1} and strain of 3%. Parameterizations 'CG-HM' [11], 'CG' [11], 'ZA-HM' [12] and 'CG-AP'[13] are extrapolated to cover the temperature and strain rate ranges explored in this work.

The common thing for all those experiments is that the thermo-mechanical properties of tantalum were measured at similar strain rates but at temperatures well below those explored in this work. In order to compare our experimental results with previous ones, the tantalum yield strength was calculated using the Z&A constitutive equation with a strain rate of 1000 s^{-1} and strain of 3%. All parameter sets from Table 4 have been used and the results based on parameters from [11–13] are extrapolated to cover temperature range in our experiment (see Fig. 7).

As in the molybdenum case, there is a clear difference in Fig. 7 between each of the extrapolated parametrizations and the new experimental results. Again, the extrapolated results differ significantly between themselves (up to a factor of 2) in the temperature region explored in our experiment, but there is a common feature for all of them: a very weak temperature dependence of the yield strength. However, our experimental results show a much stronger temperature sensitivity, and it is interesting that they almost fully cover the range between the two extreme extrapolated curves shown in Fig. 7.

4.3. Tungsten

Table 5 shows the values of the parameters of the Z&A equation obtained in this work and previous experiments with tungsten samples.

A limited data set exists for pure tungsten behavior at elevated temperatures and high strain-rates. Chen and Grey [11] have used commercially pure rolled tungsten plate for high strain-rate (0.001–4000 s^{-1}) tests at temperatures up to 1000 °C. Their fitting procedure resulted in a set of Z&A parameters denoted as 'CG' in Table 5 (and Fig. 8 – see below).

Lennon and Ramesh [2] have measured and fitted ('LR' set in Table 5) the stress–strain curve of the samples made from heavily deformed extruded tungsten rod. The commercially obtained extruded rod had undergone about 80% reduction in area (about 60% effective strain). The samples were tested in the strain-rate range of (0.001–7000) s^{-1} and at temperatures ranging from 27 to 800 °C.

Table 5
Comparison between this work and previous results [2,11] on Z&A model parameters for tungsten.

Parameter	CG [11]	LR [2]	This work
C_1 (MPa)	3000	2749	4711
C_2 (K^{-1})	2×10^{-3}	2.25×10^{-3}	5.97×10^{-3}
C_3 (K^{-1})	1×10^{-4}	9.05×10^{-5}	6.24×10^{-4}
C_4 (MPa)	0	49.91	94.37
C_5 (MPa)	800	194.5	133
n	0.6	0.0505	0.512

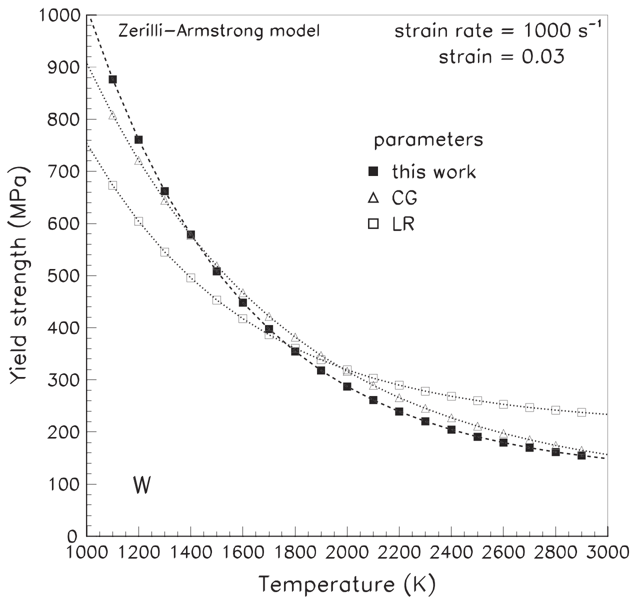

Fig. 8. Tungsten yield strength, calculated using the Z&A constitutive equation, as a function of temperature for the strain rate of $1000\ s^{-1}$ and strain of 3%. Parameterizations 'CG' [11] and 'LR' [2] are extrapolated to cover the temperature and strain rate ranges explored in this work.

Tungsten samples for the tests performed by Dummer et al. [21] were subjected to different heat treatments. The as-received tungsten were made by pressing the tungsten powder at 1200 °C and then sintered at 2600 °C. The portions of the final samples were annealed at 1750 °C, 2600 °C and 2800 °C. The experiments were performed at room temperature only with the strain-rate ranging from 0.001 to $4000\ s^{-1}$. The parameters of the Z&A equation obtained for as-received tungsten samples were practically the same as in the Chen and Grey experiment. In the case of annealed tungsten the yield strength was reduced by about 40%.

Once more, one can see that the thermomechanical properties of tungsten were measured at temperatures well below the temperature region explored in this work. In order to compare our new results with these, the tungsten yield strength was calculated using the Z&A constitutive equation for the strain rate of $1000\ s^{-1}$ and strain of 3% (characteristic values in this experiment) and plotted in Fig. 8 as a function of temperature. All parameter sets from Table 5 have been used and the results based on parameters from [2,11] are extrapolated to cover the temperature range of our experiment. Visual inspection of Fig. 8 reveals an excellent agreement between this work and the 'CG' parametrization of the Z&A equation while the 'LR' parametrization has a different slope.

4.3.1. Hot forged tungsten results

In order to study a material strength dependance on details of the manufacturing process the tests have been performed with tungsten samples made from the hot forged bars which have been centerless ground down to the size (0.6 mm diameter in this case) needed for application of the method described in Section 2.

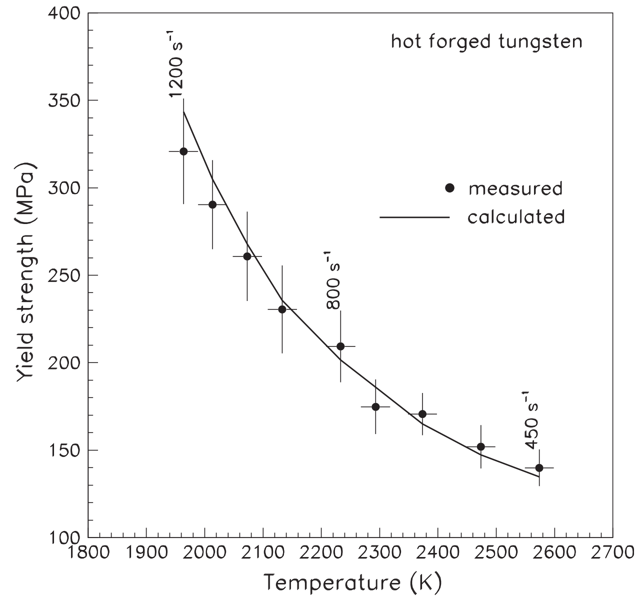

Fig. 9. Comparison between measured yield strength of hot forged tunsgten bar of 0.6 mm diameter (filled dots) and the results of calculation (solid line) based on the measured temperatures and strain rates (characteristic values indicated) and using the Z&A constitutive equation and set of parameters obtained in the tunsgten wire tests (see Table 2).

This was done to see if there is any difference between the strength of the drawn wire and hot forged bar at high temperatures and high strain rates. The results of the tests are shown in Fig. 9 (filled dots). The experimental values are compared with the results of calculation (solid line) based on the measured temperatures and strain rates (characteristic values indicated) and using the Z&A constitutive equation and set of parameters obtained in the tunsgten wire tests (see Table 2). Excellent agreement between the measurement results for the hot forged tungsten and calculations (based on the drawn wire parameters values) indicates that manufacturing particularities do not play an important role at high strain rates and very high temperatures.

4.3.2. Concluding remarks

Comparison of the test temperature dependence of yield strength based on the parametrization obtained from the Z&A model shows that the difference for tungsten between the present results and the extrapolated values from the literature is quite small compared to that for molybdenum and tantalum (see Figs. 6–8). In other words, the (comprehensive) C_4 and C_5 terms in the Z&A description produce for the three tungsten cases relatively small differences in athermal stresses as shown in Fig. 8. Fig. 6 for molybdenum shows somewhat pronounced, and Fig. 7 for tantalum much more pronounced, differences in the curves mainly as a result of different athermal stress contributions (also including the C_5 work hardening stress term). Further, as mentioned in Section 2, the tungsten samples have been additionally stress relieved at about 400 °C and this may also influence the results of the experiment.

When discussing the applicability and limitation of the Z&A model results, and especially their extrapolation, one must take into account the different sorts of material deformation mechanisms and their temperature dependence. For example, tantalum is known for being able to be strengthened by athermal substructure development [22]. An additional concern mentioned in Ref.

[12] is that the different yield point behaviors of bcc metals is not taken into account in the Z&A equations. The yield point behavior is not observed for pre-strained and/or un-annealed material and therefore is not a problem. Such interstitial-solute-associated yield points are relatively more pronounced in wire-type specimen tests where strains of $\sim$0.03 can easily be measured and become increasingly important at lower temperatures. In the temperature range between 0.2 and 0.5 of the melting temperature, interstitial strain-ageing behavior also occurs and generally raises the material strain hardening behavior in a local temperature range determined by the solute diffusivity. The effect is additive to the Z&A or other description but should be negligible for our relatively high strain-rate deformations [23].

5. Summary

An analysis of the extensive set of high strain rates measurements of the yield strength of molybdenum, tantalum and tungsten at the record high temperatures (in the range of 1350–2700 K) has been performed. The strain-rates in all the tests were in the range from 500 to 1500 s^{-1}. The parameters for the constitutive equation developed by Zerilli and Armstrong have been determined from the experimental data. Also, it has been found that the Johnson–Cook model is inadequate for describing our test results.

The parametrization obtained from the Zerilli–Armstrong model has been compared with the extrapolated parametrizations obtained in the tests at lower temperatures. The inspection of molybdenum results reveals that the extrapolated results of the previous experiments differ significantly between themselves (up to a factor of 5) in the temperature region explored in our experiment while our set of data lies between these sets. Similar conclusion is valid for the tantalum tests where, in addition, our results show a much stronger temperature sensitivity than the extrapolated parametrizations obtained from the tantalum tests at lower temperatures. In the case of tungsten, our results and the extrapolated Chen–Gray parametrization agree very well.

It has also been determined that there is no difference between the strengths of the tungsten wires and hot forged tungsten bars in the temperature and strain rate regions explored here. This means that the Zerilli–Armstrong model and parameters values given in Table 2 can be used for prediction of the behavior of bulk samples of tungsten in high strain rate applications at the temperatures higher than 1000 °C.

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