APPLICATION OF MINIATURIZED DIRECT IMPACT COMPRESSION METHOD IN CHARACTERIZATION OF MECHANICAL BEHAVIOR OF MATERIALS

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Abstract: The paper presents the results of tests on polycrystalline tantalum at very high strain rates ($7.5 \mathrm{x} 10^4$ s^{-1}). The measurements were carried out using miniaturized Direct Impact Compression Test (DICT) method. The transmitting bar diameter was 3mm, and the tested specimens were cylindrical shape of 1.5 mm diameter and 0.55 mm thickness. A numerical model of the testing stand was developed in the ABAQUS environment to trace the phenomena occurring during specimen deformation and to evaluate their influence on the final result. The test stand dimensions and the test parameters used in the calculations were this same as for DICT experiments. The results of computer simulations demonstrated good agreement with experimental results, which proves that the Finite Element Method (FEM) reproduces well the behavior of the stand and can be applied in analyses performed to find the reasons of errors in plastic stress flow measurements.

Keywords: Direct Impact Compression Tests, Tantalum, high strain rates, compression tests, Hopkinson bar

1 INTRODUCTION

Miniaturized DICT method allows testing mechanical properties of materials in the strain rate range of 10^4 s^{-1} to $1.5 \mathrm{x} 10^5$ s^{-1}, i.e. much higher than the strain rate achievable in the Split Hopkinson Pressure Bars (SHPB). This enables a fuller description of material behavior in the area of deformation under dynamic conditions. The results are then used during designing and testing of elements and impact protection structures, such as armors, projectile-proof vests, helmets etc.

This study aimed at developing a numerical model of a miniaturized DICT testing stand, to trace the phenomena occurring during the testing of specimens and to validate the results. Deformation at very high strain rates is accompanied by a number of unfavorable phenomena which influence the results, such as friction, inertia, adiabatic heating, excitation of elastic waves. The compression test of a tantalum specimen was performed to check the agreement of the developed model predictions with experimental data. The results were compared with data calculated in the ABAQUS environment.

2 DIRECT IMPACT COMPRESSION METHOD

An idea to remove the input bar of a typical SHPB [Kolsky, 1949] testing stand was first presented in 1970 [Dharan et al., 1970] and is called a DICT. The basic advantage of this solution is a significant increase of specimen strain rate calculated approximately as V_0/l_0. This, combined with a miniaturized testing stand, gives the strain rates up to $1.5 \mathrm{x} 10^5$ s^{-1}, at the projectile velocity V_0 of 150 m/s and the initial specimen length l_{S0} equal to 1 mm. Reduction of specimen length also entails the reduction of its diameter in order to ensure the specimen shape coefficient l_{S0}/d_{S0} at the 0.5 level, which is necessary to minimize the friction and inertia effects [Davies et al., 1963]. Reduced specimen dimensions lead to the necessity of reducing the overall testing stand dimensions which gives a number of advantages, such as: reduced time to achieve homogeneous strains in the specimen, reduced deformation gradients caused by elastic waves along the compression direction, decreased effects of longitudinal and transversal inertia, reduced elastic dispersion of longitudinal wave.

The literature provides descriptions of miniaturized testing stands with a bar diameter below 5mm used for testing of dynamic properties of aluminum and aluminum alloys, copper, iron, and also tungsten, using both Split Hopkinson Pressure Bars (SHPB) method [Lindholm, 1978; Follansbee et al., 1984] and Direct Impact Method (DIM) [Gorham, 1980; Shioiri et al., 1995; Kamler et al., 1995]. The highest strain rates ($2.5x10^5$ s^{-1}) were achieved by Kamler [Kamler et al., 1995], using the testing stand with a 1.5mm diameter bar for testing properties of copper specimens of 0.3mm in length and 0.7mm in diameter. The experiments presented in this paper were performed using new design of the DICT stand [Malinowski et al., 2007], in which the diameter of measuring bar was reduced to 3mm [Malinowski, 2010]. The tests were performed on polycrystalline tantalum the mechanical properties of which are relatively well known in a range of static and dynamic loads up to about 10^4 s^{-1} [Hoge et al., 1977; Zerilli et al., 1990], but in the case of deformation at very high strain rates (above 10^4 s^{-1}) the only available data have been obtained using pressure shear plate impact at the strain rate of about 10^6 s^{-1} published by Dupfrey and Clifton [Duprey et al., 1998], but there are no results for the range from 10^4 s^{-1}to10^5 s^{-1}, obtained with the Hopkinson bar.

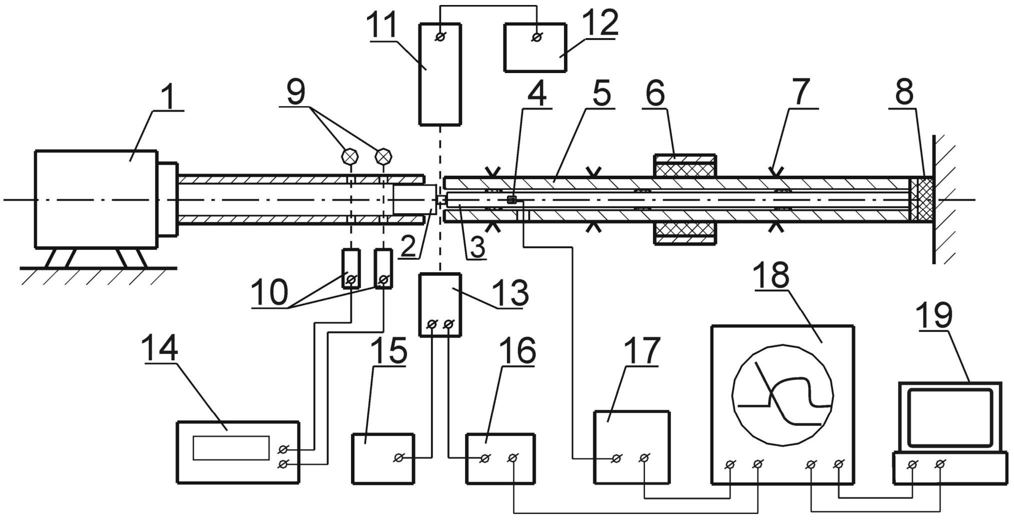

Figure 1; General scheme of DICT, 1 – air gun; 2 – striker; 3 – transmitter bar; 4 – SR gage; 5 – decelerator tube; 6 – main support; 7 – supports; 8 – dumper; 9 – light sources; 10 – photodiodes; 11 – laser diode; 12 – supply of 11; 13 – photodiode (displacement measurement); 14 – time counter; 15 – supply unit of 13; 16 – DC amplifier; 17 – SR amplifier; 18 – digital oscilloscope; 19 - PC.

A diagram of the testing stand used to test mechanical properties of materials at very high strain rates is shown in Fig.1. The main component of the system is a supporting bar of 3 mm diameter and 248 mm length, made of maraging steel Marval 18H with strength of 1900 MPa. Teflon bearings supporting the bar are placed every 40mm to prevent the bar from buckling. A muffler is placed at the end of the bar to absorb mechanical wave which is propagated along the bar. Strain gauges with gauge length of 0.6 mm were bonded symmetrically on both sides of the bar, 22 mm from the edge, on which the tested specimen is placed. The strain gauges were connected in series to eliminate the influence of bending effect on a measurement result. The measurement system of strain gauge bridge has a wide transmission band to ensure correct operation of very short (lasting a dozen or so μs) signals. The projectile made of maraging steel (11 mm diameter and 12.5 mm length) can be accelerated in a pneumatic launcher to the velocity within a range from 20 m/s to 150 m/s.

3 RESULTS OF TANTALUM TESTS

Experiments on tantalum under compressive loads at very high strain rates were conducted using specimens of diameter d_{S0} = 1.5 mm and length l_{S0} = 0.55 mm. The stress vs. time, strain vs. time and strain rate vs. time curves obtained with a miniaturized DICT method are presented in Fig. 2. The recording time for the data used in subsequent analyses is equal to 6μs. The remaining part of recorded data not useful to determine the material characteristics reflects the projectile breaking process in a thrust sleeve and projectile elastic rebound off the sleeve. The specimen strain rate is reduced from $8\text{x}10^4$ s^{-1} to $7\text{x}10^4$ s^{-1}. It is caused by plastic deformation of material leading to increase of contact areas between specimen and supporting bar. The assumed average strain rate was $\dot{\varepsilon} = 7.5\text{x}10^4$ s^{-1}. The specimen deformation process, in form of the true strain vs. time curve is almost linear. The curve inclination increases over time, and as a consequence the strain rate also increases. It has to be notices that the strain rate is determined as a derivative of the nominal strain. The true stress curve in the specimen shown in Fig. 2 and calculated on the basis of electrical signal from strain gauge bonded to the transmission bar has very strong oscillations caused by reflecting elastic wave inside the specimen. The oscillation magnitude is reduced for subsequent waves from 400MPa to about 200 MPa for the last, fourth wave. As a result of change of sample geometry during deformation the distance between summits of successive oscillations is reduced from 1.68 μs to 1.25 μs.

4 NUMERICAL ANALYSIS

Application of the Finite Elements Method (FEM) seems to be a very good way to check the correctness of experiments carried out, particularly in the case of a miniaturized DICT stand where the usage of high-speed cameras to monitor the experiment is impossible due to small dimensions of the specimen and a very short deformation time. The DICT does not provide an opportunity of using additional data collection techniques to verify the correctness of the results (e.g. signal from strain gauges the initiating and transmitting bar, and in addition a signal from the LORD transducer), because this test stand does not have an input bar.

Computer simulation in the ANSYS environment was applied in the paper [Sasso et al., 2008] to reduce an influence of adiabatic heating, dispersion effects, varying deformation speed, inhomogeneous stresses of neck forming in dynamic tension process on the measurement results. The parameters of selected constitutive equations of tested material were changed during the analysis to minimize mean square error between the results of simulation and experiment. Numerical methods can also be used to trace in detail the process of elastic wave propagation and dispersion in the Hopkinson method. An influence of pulse shaper material and geometry on the forming of the loading wave oscillations was examined in the paper [Ramirez et al., 2006].

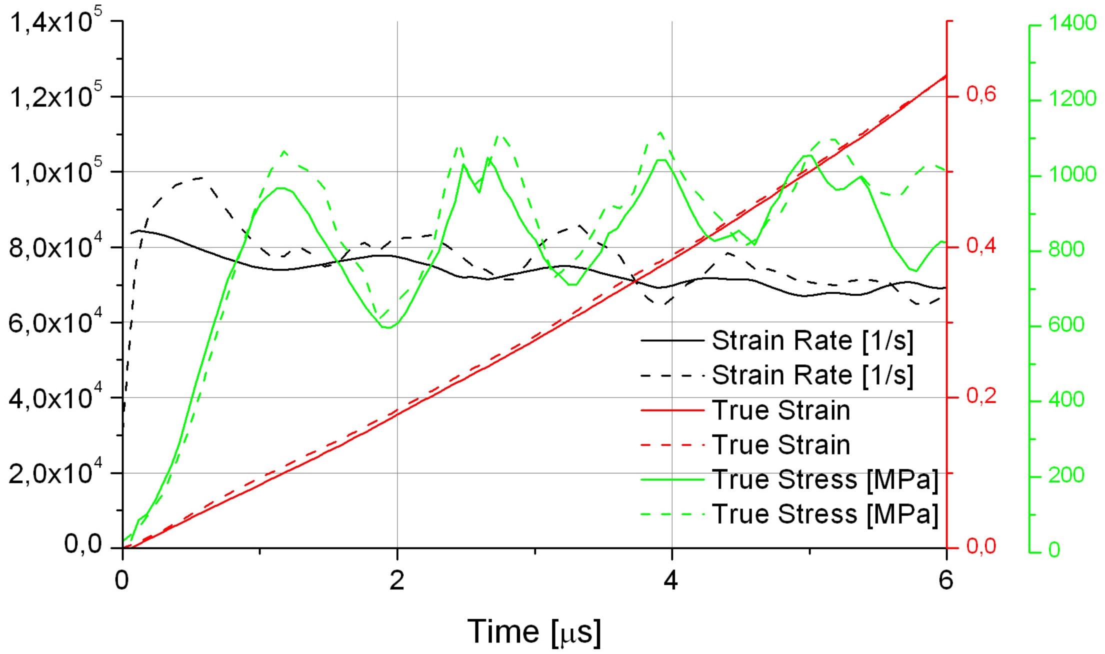

Figure 2; The stress vs. time, strain vs. time and strain rate vs. time curves of tantalum determined using the miniaturized DICT method (solid line) and calculated using FEM (broken line).

In our study, the numerical analysis was performed to make a simulation, using the dimensions of specimen, testing stand, and parameters of test identical as those in the experiment applied. The goal was to check whether it is possible to carry out computer simulation reflecting phenomena occurring during very fast deformation of miniature specimens. A model of a miniaturized DICT test stand was prepared for numerical analyses. The basic elements of the model were: projectile, supporting bar, thrust sleeve and the specimen. The dimensions and relative position of individual model elements were the same as those on the testing stand. Boundary conditions were specified for the model: constrain of the displacement of bar and thrust sleeve fixing plane in both axes, initial specimen temperature of 298K, no exchange of heat through contact between the projectile and bar, and the initial projectile velocity. In the ABAQUS environment the axis symmetric model was applied. It reflected the effects of adiabatic heating and friction between the projectile – specimen and projectile – bar interfaces, for the friction coefficient μ=0.1. The following physical and mechanical properties of maraging steel were assumed: Young's module E_S=200 GPa, specific gravity: ρ_S=7860 kg/m^3. Moreover it was assumed that the elements of the testing stand will be subjected to elastic strain. Hence, the elastic model of material was used in the simulation. The data calculated according to the Z-A (Zerilli – Armstrong) constitutive model were used for tantalum. The model can be represented by the following equation [Zerilli et al., 1987]:

$$\sigma = c_0 + B_0 e^{-(\beta_0 - \beta_1 \ln \dot{\varepsilon})T} + K\varepsilon^n \qquad (1)$$

The following values of the equation parameters were used in calculations: c_0=30MPa, B_0=1125 MPa, β_0=0,00535 1/K, β_1=0.000327 1/K, n=0,44.

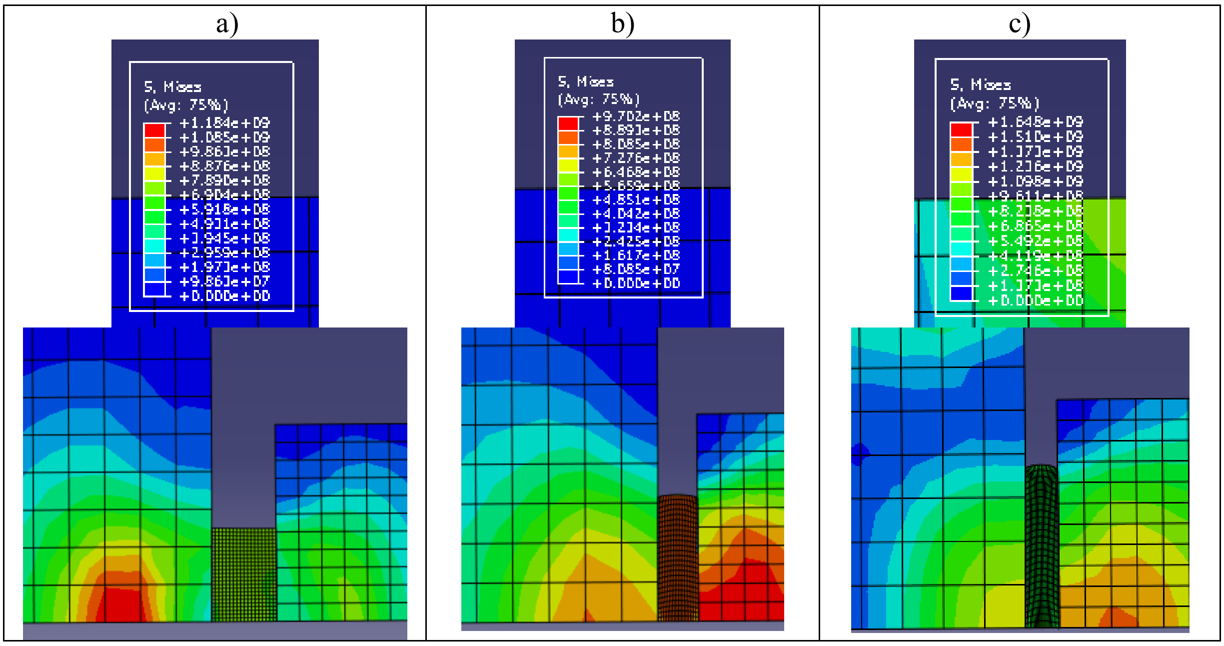

Figure 3; Distribution of reduced stresses (S. Mises) in the specimen and testing stand elements for the friction coefficient μ=0.1; l_0=0.55mm; D_0=1,5mm in successive stages of the experiment: a) t=8.4 μs, b) t=13.4 μs, c) t=15.9 μs

The successive stages of specimen deformation are presented in Fig. 3. Part (a) of these figure presents the moment when the projectile hits specimen and a process of establishing uniform strain in the specimen. It takes place directly after the impact. A part of the projectile near the specimen shows a field of large stresses which decreases with increased distance from the projectile-specimen interface. In the transmitting bar a field of high stresses is generated directly from the specimen - bar interface. Figure 3b presents distribution of stresses during plastic deformation of the specimen. The elastic wave propagation takes place in both projectile and transmitting bar. The transversal distribution of stresses in the supporting bar is very inhomogeneous near the contact, but it becomes more homogeneous as the distance from the contact increases. According to the data from literature the sufficient homogeneity is achieved at the distance of 5 diameters from the specimen-bar interface [Malinowski, 2010]. Figure 3c shows the process of projectile deceleration. This phenomenon occurs in a certain nonzero time period. Consequently, after the projectile hits the sleeve, the specimen is still subjected to deformation taking place under reducing speed which may be often significant for structural analysis. After the impact, a longitudinal elastic wave is generated in the decelerator sleeve, similarly as in the transmitting bar.

5 SUMMARY

The paper presents the result of compression test of polycrystalline tantalum using a miniaturize DICT stand. The experimental results were compared with those of computer simulation (Fig. 2) conducted in the ABAQUS environment, on the basis of numerical model of the testing stand elaborated. Comparison of FEM predictions with experimental data exhibits relatively good agreement, ie.

- the strain rate is slightly reduced from $8x10^4$ s^{-1} to $7.5x10^4$ s^{-1} over 6 μs of the test,
- the strain vs. time curve has a very similar shape (at 6^{th} μs of the test ε=0.65),

- in both cases, the stress vs. time curves have characteristic oscillations, amplitude and average level are comparable.

Finally may be concluded that the numerical results obtained using proposed model of miniaturized DICT exhibits reasonable good agreement with experimental data. Therefore, the model seems to be applicable for investigation and analysis of the phenomena occurring during the specimen deformation, under dynamic loading.

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