EXPERIMENTAL INVESTIGATION OF MECHANICAL PROPERTIES OF COPPER AT HIGH-STRAIN-RATE LOADING CONDITIONS

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Summary

Experimental studies on mechanical properties of Cu-ETP copper under strain rates above 2.6 x 10^3 s^{-1} are presented in this work. The electromagnetic expanding ring experiment and impact Taylor test were used as the tools for examining the dynamic behaviour of selected copper. Experimental study by using above-mentioned techniques was performed to assess a methodological correctness of experiments in which laboratory apparatuses developed at Military University of Technology were used.

Keywords: expanding ring test, Taylor impact test, high-strain-rate deformation.

BADANIA DOŚWIADCZALNE WŁAŚCIWOŚCI MECHANICZNYCH MIEDZI W WARUNKACH DYNAMICZNEGO ODKSZTAŁCENIA

Streszczenie

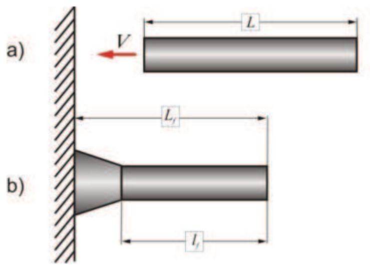
W artykule przedstawiono badania doświadczalne właściwości mechanicznych miedzi Cu-ETP w warunkach dynamicznego obciążenia. Badania dynamiczne wykonano za pomocą elektromagnetycznego testu pierścieniowego i zderzeniowego testu Taylora. Celem badań była ocena poprawności metodycznej przeprowadzonych badań, podczas których zastosowano aparaturę laboratoryjną, opracowaną w Wojskowej Akademii Technicznej.

Słowa kluczowe: test pierścieniowy, uderzeniowy test Taylora, deformacja dynamiczna.

1. INTRODUCTION

Many engineering applications, such as metal forming, armour penetration, shaped charge jet generation, crash absorbers deformation in cars etc., may benefit from an understanding of the influence of deformation velocity on mechanical materials properties. For over the past six decades many investigators have made an effort to reveal factors influencing on strength and ductility under dynamic plastic deformation [1]. For this purpose, many different experimental techniques have been developed, among which split Hopkinson pressure bar (SHPB) method is the most common [2, 3]. However, the method of Hopkinson has many limitations, so many other experimental methods were used to examine the behaviour of materials under dynamic deformation. For these methods among others may include impact Taylor test [4] and the electromagnetic expanding ring test [5].

The impact Taylor test was developed for determining, in simple way, the yield stress of materials under dynamic compression. The method involves impacting a rigid circular cylinder (material sample) against a rigid target and making post-impact measurement of the deformed shape of specimen (Fig. 1). On the basis of measuring the impact velocity and the degree of deformation of cylindrical samples can be calculated the value of dynamic yield stress using the equation, which was derived by Taylor [4] (Fig. 1).



$$Y = \frac{\frac{1}{2}\rho V^2\left(1-\frac{l_f}{L}\right)}{\left(1-\frac{L_f}{L}\right)\ln\left(\frac{L}{l_f}\right)}$$

Fig. 1. Schematic illustration impact Taylor experiment and equation for estimating the dynamic yield point *Y*, where: ρ - density of sample material cylinder, *V* - velocity of impact; *L* - length of the sample before the impact; L_f - total length of the sample after the collision, l_f - the length of undeformed part of the sample

An electromagnetic expanding ring technique is more complex and demanding application of advanced test equipment and measurement systems, such as a velocity interferometer system for any reflector (VISAR) or a high-speed camera. Generally, this method is based on recording of the motion of the thin-walled ring made from the tested material, which was launching due to electromagnetic forces induced during discharging of capacitors through solenoid coil (Fig. 2).

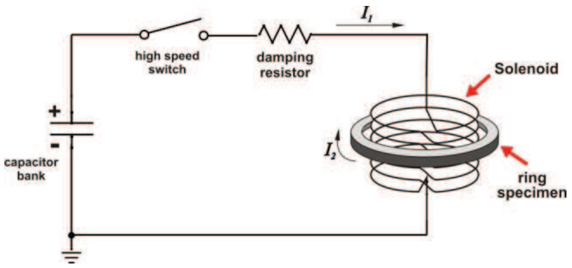


Fig. 2. Diagram of the arrangement for electromagnetic ring expansion

By measuring the radial displacement $r(t)$ or velocity history $v(t)$ of the ring specimen for inertial stage of expansion, the circumferential stress σ_θ and true strain ε_θ for ring material under high-strain rate tension conditions can be determined at the imposed strain rate using relationships presented below:

$$\sigma_\theta = -\rho r \frac{\partial^2 r}{\partial t^2}, \qquad \varepsilon_\theta = \int_{r_0}^{r} \frac{dr}{r} = \frac{\ln r}{r_0}. \qquad (1)$$

where: ρ - density of sample material cylinder, r_0 and r – initial and current radius of ring specimen, respectively.

In the paper, the experimental study for Cu-ETP copper was carried out with the use of the above mentioned techniques to assess a methodological correctness of experiments, in which laboratory apparatuses developed at Military University of Technology were used.

2. EXPERIMENTAL PROCEDURE

The studies on mechanical properties of Cu-ETP copper under strain rates of the order of 5 x 10^3 s^{-1} were performed by using apparatuses presented in Fig. 3. The laboratory arrangement for impact Taylor test (Fig. 3a) consists of pyrotechnic launching system, the maraging steel target plate with polished surfaces, and recording system, which is composed of high-speed camera and illumination system. On the other hand, an experimental setup for expanding ring test presented in Fig. 3b, principally, consists of three main components; *pulse power system* containing 240 µF capacitors bank and two impulse thyristors, *loading assembly*, and finally *charging system* (invisible in Fig 3b). The solenoid with the ring sample is inserted into a loading assembly. It consists of two 20 mm polycarbonate plates with cavities, which support the solenoid with the copper ring and a wax ring at the outside of the cavity. The wax ring plays a role of a capture medium for fragments generated during fracture of the ring sample.

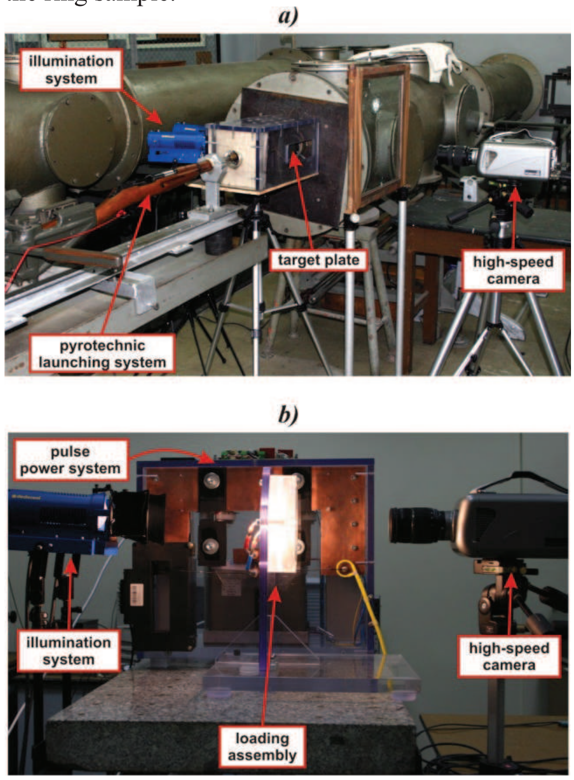


Fig. 3. View of the arrangement for impact Taylor test and electromagnetic ring experiment

As is the case of experimental setup for Impact Taylor test, displacement of the ring during expansion process was recorded with the high-speed camera (Fig. 3), whereas the ring velocity history was calculated from the high-speed images using the TEMA Automotive software. To obtain good accuracy of the ring expansion velocity with the use of available equipment, the observation field of high-speed camera was limited to a small area, in which there was visible only a moving ring segment and two scaled points (Fig. 4).

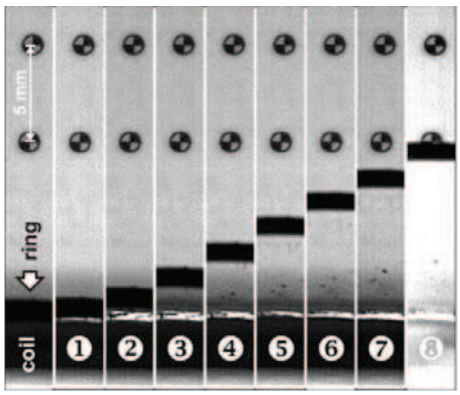


Fig. 4. The sequence of images showing the copper ring segment motion

Cylinder and ring samples were machined from the cold-rolled Cu-ETP copper bar with 40-mm diameter. The engineer properties of tested copper are presented in Table 1. The dimensions of cylindrical samples were 8 mm x 40 mm, whereas the rings had the mean diameter of 32 mm, and the cross-sectional area of 1.5 mm x 1.5 mm.

Table 1. Mechanical properties of the cold-rolled Cu-ETP copper

Ultimate tensile strength R_m	[MPa]	263
Yield strength $R_{0,2}$	[MPa]	239
Elongation A_5	[-]	0.30
Hardness	HV1	90
Average grain size	[µm]	55

3. RESULTS AND DISCUSSION

In Figure 5, the selected images recorded by using digital high-speed camera and photographs of samples after tests are arranged to illustrate the process of plastic deformation of the sample material in both Taylor test and ring experiment conditions.

As it is seen in Fig. 5, the Taylor specimen made of Cu-ETP copper was 'mushroomed' by the impact, and its geometric profile is typical for metals with good ductility and high strain-hardening exponent. Good ductility of the studied Cu-ETP copper is also confirmed by the expanding ring test. The copper ring seen in Fig. 5 expands radially for a relatively long time and deforms plastically without disturbing the integrity of material structure (fracture strain ≈ 39%), and next the ring breaks into small fragments.

Quantitative results of the dynamic tests were collected in Table 2 and 3, where, moreover, there are included calculation data on the basis of which the dynamic yield stress Y and circumferential stress σ_θ were determined. It should be noted that, in the case of Taylor's test, the dynamic yield stress was determined in accordance with the classical methodology proposed in [4] (exact analysis), while the plastic flow stress at the ring experiment were calculated using the equation (1) and for strain equal to 0.25 (it is strain for which a ring sample deforms only due to inertia forces).

For the Taylor impact test, the average value of dynamic yield stress for the tested copper is 342 MPa, while the plastic flow stress at 0.25 strain extracted form ring test is equal to 341 MPa. Generally, these results show that the dynamic plastic flow stress of copper increased significantly compared to the corresponding static stress yield.

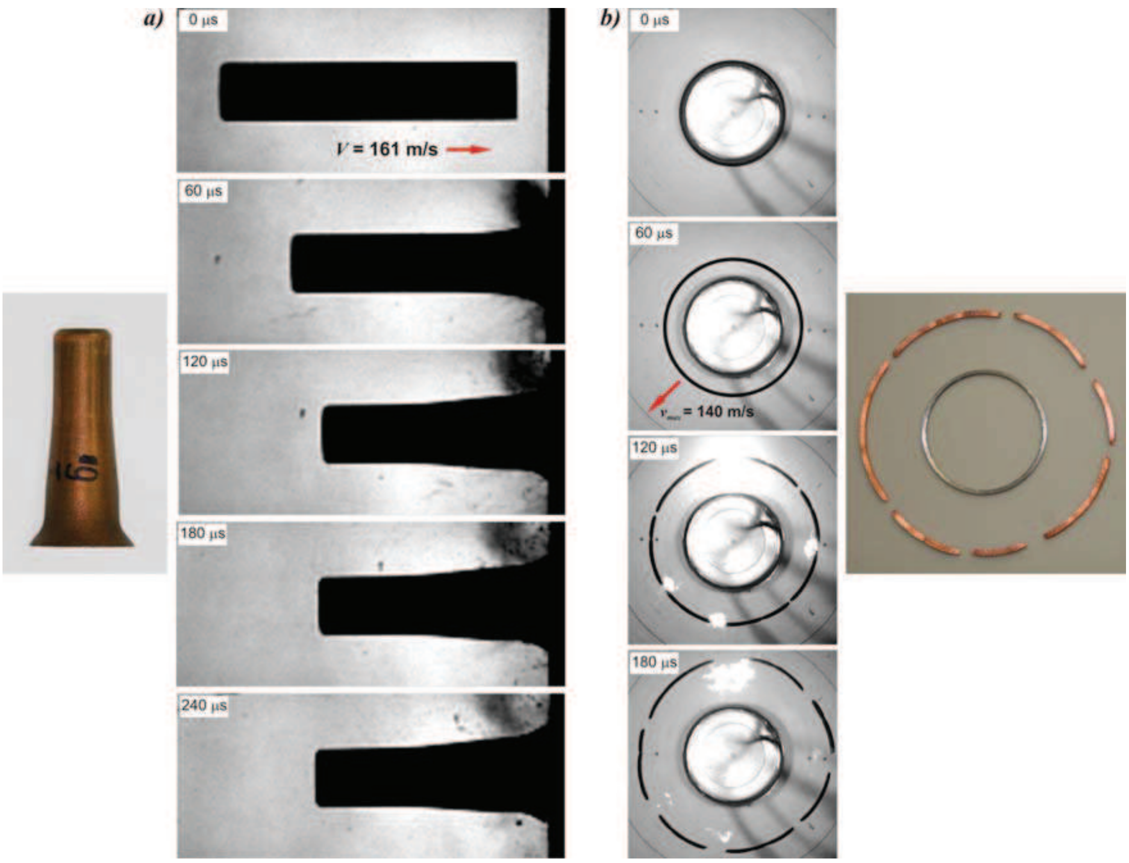


Fig. 5. The sequence of images showing the deformation of copper cylinder (a) and ring specimen (b) under high-strain-rate loading conditions

Table 2. Experimental and calculated data extracted from impact Taylor for the cold-rolled Cu-ETP copper

Test no.	Original length [mm]	Velocity V [m/s]	Overall length of the sample after test L_f [mm]	Undeformed sample length l_f [mm]	Strain rate [s^{-1}]	Dynamic yield stress Y [MPa]
07	40.017	162.7	30.969	12.15	2,92 x 10^3	348
08	40.023	150.7	31.964	12.15	2,70 x 10^3	337
09	39.915	161.2	30.931	10.95	2,78 x 10^3	332
10	40.014	185.5	29.121	9.07	3,00 x 10^3	338
11	40.050	141.8	32.692	13.46	2,67 x 10^3	342
12	39.869	132.5	33.399	14.76	2,64 x 10^3	352
					Average value	**342**

Table 3. Experimental and calculated data extracted from electromagnetic ring test for the cold-rolled Cu-ETP copper

Test no.	Max. expansion velocity [m/s]	Deceleration $\frac{\partial^2 r}{\partial t^2}$ [m/s^2]	Strain rate for $\varepsilon_\theta = 0,25$ [s^{-1}]	Plastic flow stress σ_θ for $\varepsilon_\theta = 0,25$ [MPa]
07	139.4	1744803	5,74 x 10^3	323
08	142.9	1890156	5,93 x 10^3	350
09	140.4	1892992	5,88 x 10^3	350
10	141.0	1833737	5,83 x 10^3	339
			Average value	**341**

This behaviour of copper under dynamic loading is typical and confirmed in numerous scientific publications [e.g. 3, 4]. Moreover, the level of plastic flow stress received for Cu-ETP is similar to flow stress obtained for resembling types of copper. For example, the obtained stress value extracted from Taylor impact test for Cu-ETP copper is very consistent with the analogous value for hardened OFE copper ($Y = 335$ MPa) presented in [6] (test conditions; the specimen is initially 7.6 mm in diameter and 57.1 mm long, the impact velocity was 189 m/s). Similarly, the good agreement between the obtained results and the data found in the literature was achieved for electromagnetic ring test. For example, in the work [7], flow stress for OFE copper determined by using electromagnetic ring experiment was approximately 345 MPa at 0.25 strain (Fig. 1, page 2339 in [7]), whereas in the present work, flow stress for Cu-ETP is 341 MPa at the analogues deformation level.

Based on the above-mentioned comparative analysis, generally, it can be concluded that the developed apparatus can deliver reliable results of experimental materials studied under high strain rate loading conditions. Results presented here also prove the methodological correctness of applied measurement techniques and calculation procedures.

4. SUMMARY

The impact Taylor test and electromagnetic expanding ring experiment were presented in this paper. The main goal our studies presented in this paper was assessment of methodological correctness of above-mentioned experiments in which the laboratory apparatuses developed at Military University of Technology were used. Tests were performed on Cu-ETP, for which dynamic properties are available in the literature. It was found very good agreement of the results of our experiments with similar results presented in the literature. Based on this observation, it can generally state that the developed apparatus and applied measuring procedures ensure methodological correctness and the reliability of the experimental data obtained during high strain rate testing.

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