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Experimental investigations of visco-plastic properties of the aluminium and tungsten alloys used in KE projectiles

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Abstract. The main aim of studies on dynamic behaviour of construction materials at high strain rates is to determine the variation of mechanical properties (strength, plasticity) in function of the strain rate and temperature. On the basis of results of dynamic tests on the properties of constructional materials the constitutive models are formulated to create numerical codes applied to solve constructional problems with computer simulation methods. In the case of military applications connected with the phenomena of gunshot and terminal ballistics it's particularly important to develop a model of strength and armour penetration with KE projectile founded on reliable results of dynamic experiments and constituting the base for further analyses and optimization of projectile designs in order to achieve required penetration depth. Static and dynamic results of strength investigations of the EN AW-7012 aluminium alloy (sabot) and tungsten alloy (penetrator) are discussed in this paper. Static testing was carried out with the INSTRON testing machine. Dynamic tests have been conducted using the split Hopkinson pressure bars technique at strain rates up to $1{,}2 \cdot 10^4\ \mathrm{s}^{-1}$ (for aluminium alloy) and $6 \cdot 10^3\ \mathrm{s}^{-1}$ (for tungsten alloy).

1 Introduction

The subcalibre kinetic energy (KE) projectile is the most advanced and complicated in design engineering type of artillery ammunition. The APFSDS projectile consists of the following components: rod penetrator, sabot, fin stabilizer and ballistic cap (Fig. 1).

The sabot transfers the pressure of the gunpowder combustion products on the lateral surface of the rod penetrator in order to increase its muzzle velocity, and thereby it causes increase of the impact velocity of the rod penetrator in the target. The rod penetrator and sabot are dynamically loaded by the pressure of the combustion products of the gunpowder and the inertial forces, which are generated by the projectile acceleration in the gun barrel during firing. The modern subcalibre projectiles experiences a pressure over 400 MPa and an extremely high acceleration about 70 000 g. For this reasons ensuring in-bore the correct working of the projectile under such extremely dynamic loads becomes a difficult strength problem (see fig. 2).

The main aim of studies on dynamic behaviour of construction materials at high strain rates is to determine the variation of mechanical properties (strength, plasticity) in function of the strain rate and temperature. On the basis of results of dynamic studies on the properties of constructional materials the constitutive models are formulated to create numerical codes applied to solve constructional problems with computer simulation methods. In the case of military applications connected with the phenomena of gunshot and terminal ballistics it is particularly important to develop a model of strength and armour penetration with KE projectile founded on reliable results of dynamic experiments and constituting the base for further analyses and optimization of projectile designs in order to achieve required penetration depth. The development of material strength model containing the description of processes of crack creation and deformation of its structure together with the range and the strain rate caused by dynamic loads in the wide range of temperatures allows to create the computer code reflecting in computer simulations the real dynamic processes of material deformation for high strain rates. The measurements of mechanical properties of constructional materials are taken during tensile, compression or torsion tests of material specimens. During tests conducted on standard testing machines the mechanical parameters of material are determined at average strain rate of $5\ \mathrm{s}^{-1}$. By using testing machines of special design it is possible to determine the mechanical parameters of material for strain rate about $200\ \mathrm{s}^{-1}$. Hopkinson bar method [1–5] is considered the most popular and simplest high strain rate test method compared to Taylor's impact test [4] and explosive loading techniques [6]. Substantially improvements have been made in the Hopkinson bar technique to introduce new test methods (7–9) and new analyses techniques [10, 11]. Static and dynamic results of strength investigations of the EN AW-7012 aluminium alloy (sabot) and tungsten alloy (penetrator) are discussed in this paper. Static testing was carried out by of the INSTRON testing machine. Dynamic tests have been realized using the split Hopkinson pressure bar (SHPB) technique at strain rates up to$1{,}2 \cdot 10^4\ \mathrm{s}^{-1}$ (for aluminium alloy) and $6 \cdot 10^3\ \mathrm{s}^{-1}$ (for tungsten alloy). It's necessary to mention that authors didn't find in the accessible literature static and dynamic properties of similar structural materials tested here used in the military armament technology.

2 The experiment methodology

To determine the mechanical properties of the aluminium and tungsten alloys the two types of specimens where used. For compressive tests were prepared 6 mm diameter cylinders with 3 mm length (for dynamic SPHB tests) and 12 mm length (for static compressive tests). The

Table 1. The components and their static (tensile) mechanical properties of the aluminium and tungsten alloy.

Aluminium alloy EN AW-7012								
Alloy components, %	Al	Zn	Mg	Cu	Mn	Cr	Fe	Si
	89,95	5,5	1,96	1,51	0,34	0,18	0,37	0,19
Mechanical properties	$R_{0,2}$ [MPa]		R_m [MPa]		A_5 [%]		*HB*	
	590		615		8,8		170	
Tungsten alloy								
Alloy components, %	W		Fe		Ni	Co		
	91,25		8,75					
Mechanical properties	R_{02} [MPa]		R_m [MPa]		A_5 [%]	*HRC*		
	Min. 1200		Min. 1300		Min. 8	Min. 38		

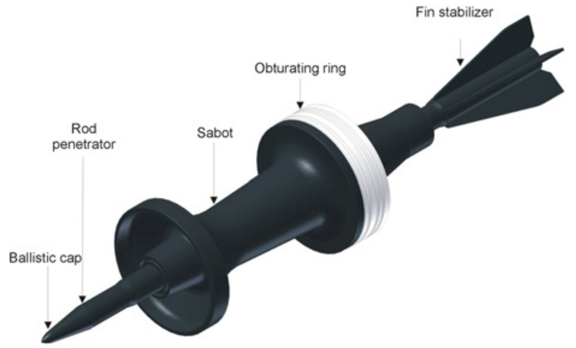

Fig. 1. Component parts of the APFSDS projectile.

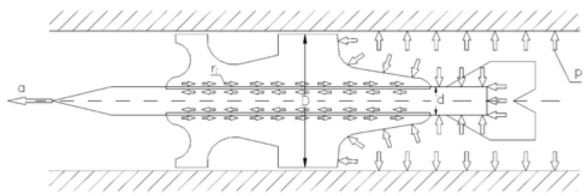

Fig. 2. Dynamic loads of the subcalibre projectile during firing (*p*- pressure, *a*- acceleration, r_i- interactions).

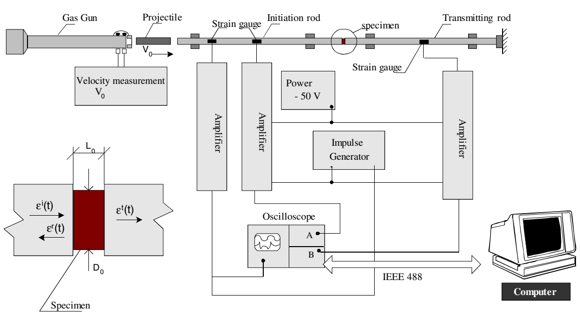

Fig. 3. Schematic of the typical compressive SPHB.

components and its static (tensile) mechanical properties of the aluminium and tungsten alloys are presented in table 1.

To determine the mechanical compressive properties at strain rates up to 1,2 $\cdot$ 10^4 s^{-1} (for aluminium alloy) and 6 $\cdot$ 10^3 s^{-1}(for tungsten alloy) the split Hopkinson pressure bar was used (Fig. 3).

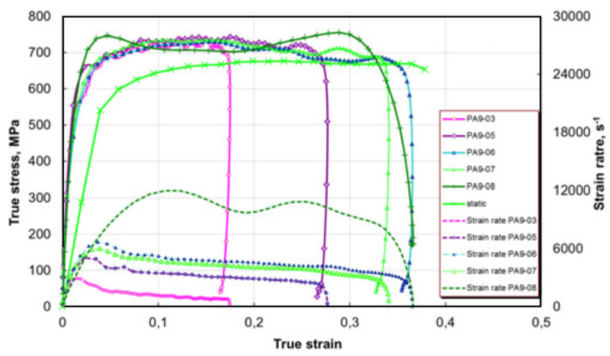

Fig. 4. The results of the SPHB tests for the EN AW-7012 aluminium alloy.

Further information about SPHB tests method are presented in [12]. It might be useful to mention that the SPHB isn't useful to determine the Young's modulus. These parameter should be defined from tensile test. Furthermore the differences between dynamic and static elastic modulus are very small for metals and crystal-structure elastic solids.

3 The test results

3.1 Aluminium alloy (sabot)

The results of the static and SPHB tests for the EN AW-7012 aluminium alloy are show in Fig. 4.

The change of the strain rate from 3 $\cdot$ 10^3 s^{-1} (PA9-03) to 6 $\cdot$ 10^3 s^{-1} (PA9-07) hasn't visible influence to strengthening of the material in initial plastic strain section. The aluminum alloy is practically insensitive on strain rate for this range. Only increasing of the strain rate to 1,2 $\cdot$ 10^4 s^{-1} (PA9-08) permit us to obtain essential difference of the dynamic yield point value.

3.2 Tungsten alloy (penetrator)

Quasi-static compressive testing was carried out with the INSTRON testing machine for constans strain rate 3 $\times$ 10^{-2} s^{-1}. The average results of strength investigations of the tungsten alloy are shown in Fig. 5.

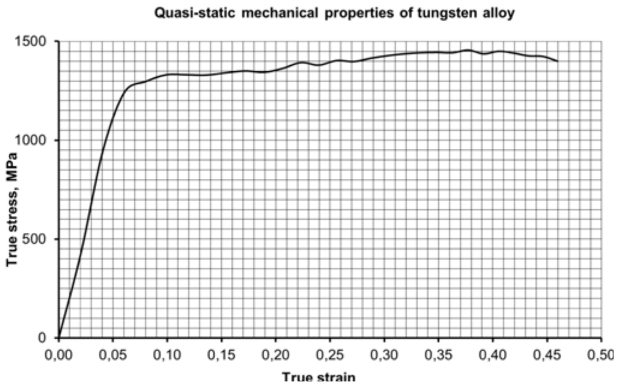

Fig. 5. The average results of the compressive test for tungsten alloy at temperature of 20°C.

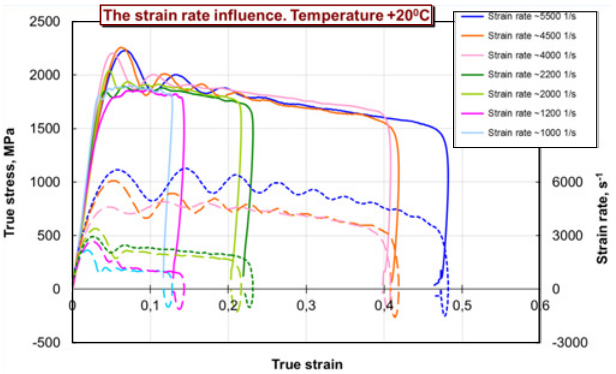

Fig. 6. The results of the SPHB tests for tungsten alloy. The strain rate influence at temperature of 20°C.

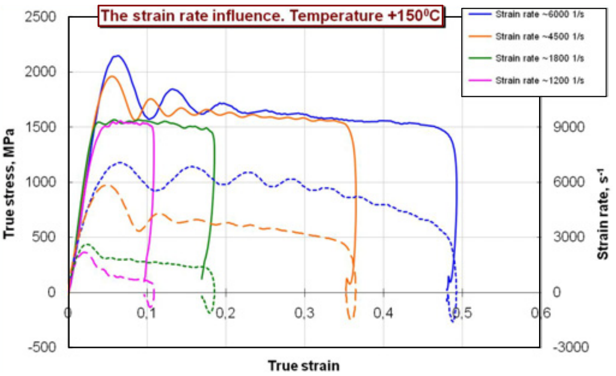

Fig. 7. The results of the SPHB tests for tungsten alloy. The strain rate influence at temperature of 150°C.

The SPHB tests for strain rates from $1 \cdot 10^3\,s^{-1}$ to $6 \cdot 10^3\,s^{-1}$ where conducted for the tungsten alloy specimens seasoned at temperatures of 20°C, 150°C and 300°C. The results of SPHB tests for tungsten alloy are presented in Fig. 6–12.

On the base of the test results the materials behaviour modelling was performed using bilinear approximations. These results are shown in Fig. 13–16.

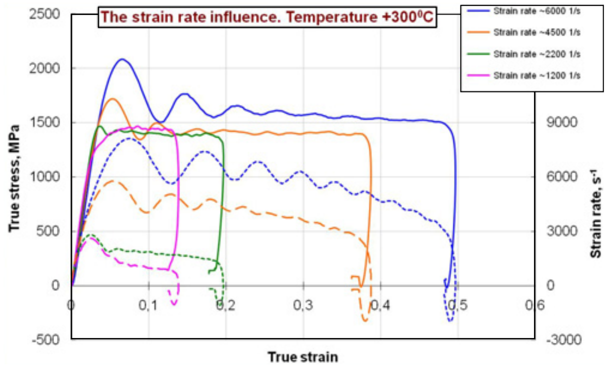

Fig. 8. The results of the SPHB tests for tungsten alloy. The strain rate influence at temperature of 300°C.

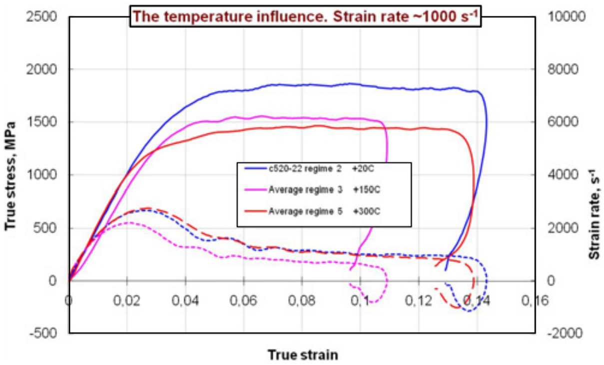

Fig. 9. The results of the SPHB tests for tungsten alloy. The temperature influence at strain rate $\sim 1 \cdot 10^3\,s^{-1}$.

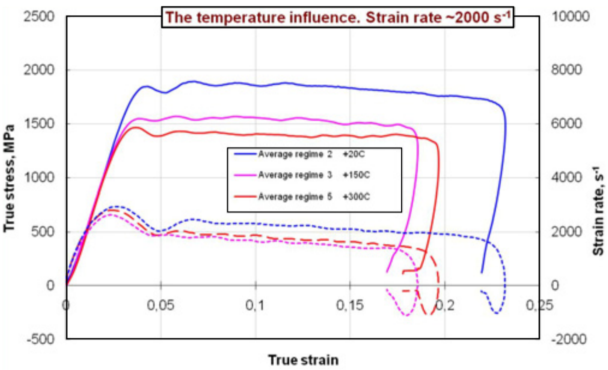

Fig. 10. The results of the SPHB tests for tungsten alloy. The temperature influence at strain rate $\sim 2 \cdot 10^3\,s^{-1}$.

4 Summary

The dynamic SPHB test results enabled to get qualitative information about stress-strain curves for EN AW-7012 alloy. They have proved, that the EN AW-7012 alloy has visco-plastic properties, but his sensitivity for strain rate is minor.

The performed tests demonstrate, that the heat weakness has influence for shape of stress-strain curves in the range of large strains (start from 0,2 value). It's connected with energy dissipation during adiabatic deformation of the specimens, what results in specimen's heating. The behavior of the EN AW-7012 alloy can be obtained by bi-linear elastic-visco-plastic model of the isotropic solid

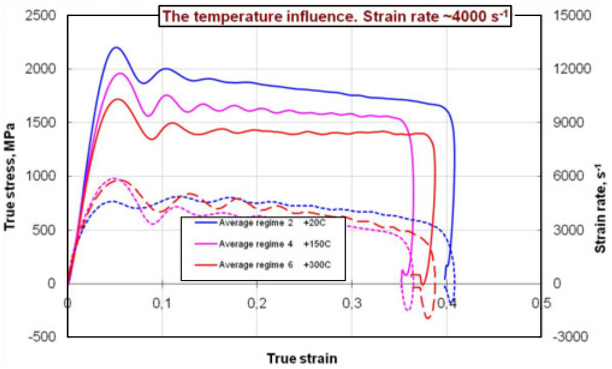

Fig. 11. The results of the SPHB tests for tungsten alloy. The temperature influence at strain rate $\sim 4 \cdot 10^3\ \mathrm{s}^{-1}$.

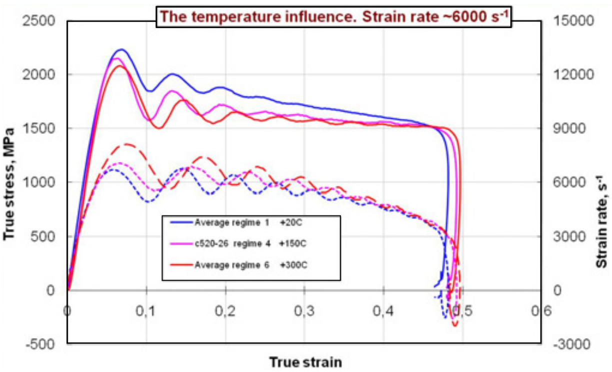

Fig. 12. The results of the SPHB tests for tungsten alloy. The temperature influence at strain rate $\sim 6 \cdot 10^3\ \mathrm{s}^{-1}$.

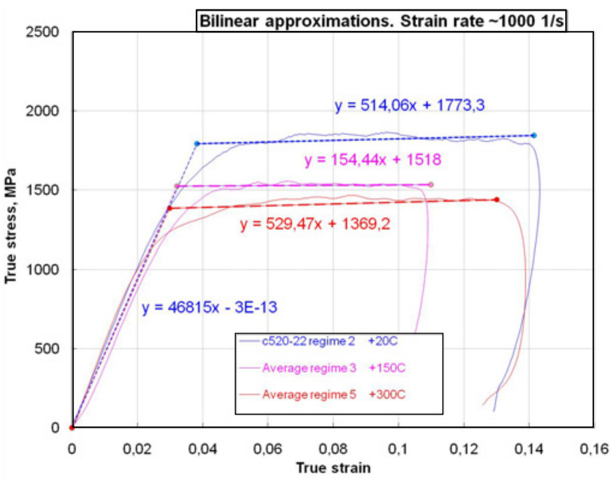

Fig. 13. The results of the SPHB tests for tungsten alloy. The bilinear approximations at strain rate $\sim 6 \cdot 10^3\ \mathrm{s}^{-1}$.

with Young's modulus ~70 GPa; and extrapolated yield point $R_{es} = 675$ MPa for static loads and $R_{ed1} = 750$ MPa for dynamic loads with strain rates up to $10^4\ \mathrm{s}^{-1}$.

The quasi-static compressive and Hopkinson tests results for examined tungsten alloy showed that at 20°C the extrapolated yield point is estimating on 1206 MPa at strain rate $\sim 3 \cdot 10^{-2}\ \mathrm{s}^{-1}$, 1773 MPa at strain rate $\sim 1 \cdot 10^3\ \mathrm{s}^{-1}$, 1967 MPa at strain rate $\sim 2 \cdot 10^3\ \mathrm{s}^{-1}$, 2058 MPa at strain rate $\sim 4 \cdot 10^3\ \mathrm{s}^{-1}$, and 2070 MPa at strain rate $\sim 6 \cdot 10^3\ \mathrm{s}^{-1}$.

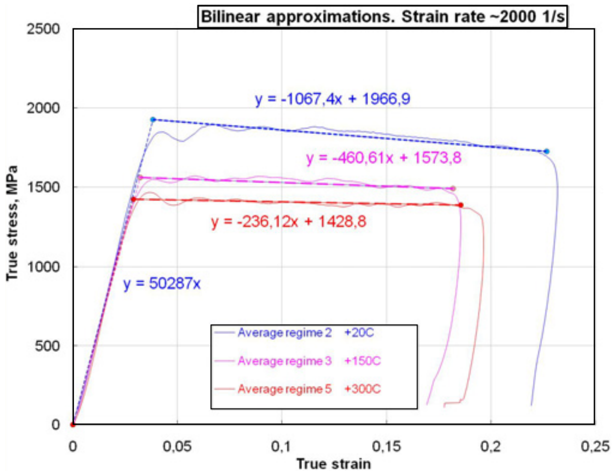

Fig. 14. The results of the SPHB tests for tungsten alloy. The bilinear approximations at strain rate $\sim 2 \cdot 10^3\ \mathrm{s}^{-1}$.

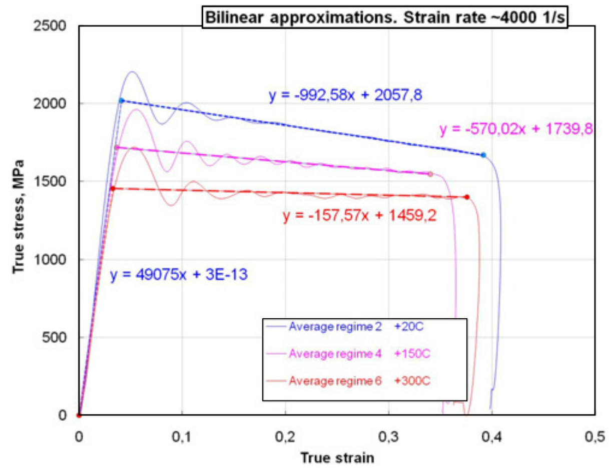

Fig. 15. The results of the SPHB tests for tungsten alloy. The bilinear approximations at strain rate $\sim 4 \cdot 10^3\ \mathrm{s}^{-1}$.

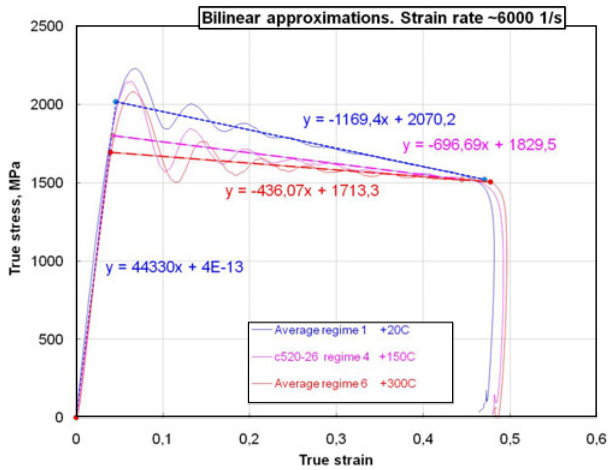

Fig. 16. The results of the SPHB tests for tungsten alloy. The bilinear approximations at strain rate $\sim 6 \cdot 10^3\ \mathrm{s}^{-1}$.

Experiment showed that increasing the rate of the deformation was increasing mechanical properties of the examined sinter.

Conducted physical experiments also showed the large impact of the thermal weakness heated to temperatures of 150°C and 300°C of specimens on character of the course of stress-strain graphs.

For dynamic loads examined at temperature of 150°C of the sinter in the rate of deformations $\sim 2 \cdot 10^3\,s^{-1}$ the extrapolated yield point amounts about 1573 MPa, and at temperature of 300°C - 1429 MPa.

For dynamic loads examined at temperature of 150°C of the sinter in the rate of deformations $\sim 6 \cdot 10^3\,s^{-1}$ the extrapolated yield point amounts about 1829 MPa, and at temperature 300°C - 1713 MPa.

First of all presented work has experimental character. In the next stage, after supplementing testing, there will be performed constitutive modelling of tested AW-7012 and tungsten alloys, particularly that aluminium alloy is practically strain rate insensitive, whereas tungsten alloy is showing the so-called plastic softening, rather than hardening.

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