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The Role of Contact Friction and Rheology in the Deformation at Plastometric Tests of Rheologically Complex Materials

Vpliv kontaktnega trenja in reologije pri plastometričnih preizkusih reološko kompleksnih materialov

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The deformation anomalies of higher orders at plastometric test are studied on easily deformable lead alloys-models of different rheological complexity by original testing methods. It is ascertained that the development of deformation anomalies depends upon the degree of rheological complexity of the material. Simple strain anomalies are due to the inadequate conditions of contact friction, while those of the higher orders results mainly from microrelief of the sample butts. Recommendations for the obtention of homogeneity of deformation at plastometric tests are given. The tests show that the deformation of rheologically complex metals develops according to laws basically different of the contemporary notions of the mechanics of plastic deformation.
Key words: plastic deformation, rheology, deformation anomalies, contact friction, homogeneous deformation

Opredeljene so deformacijske anomalije višjega reda pri plastometričnih preizkusih svinčevih spojin z različno reološko kompleksnostjo. Razvoj anomalij je odvisen od reologije materiala. Enostavne anomalije so posledica neustreznega stičnega trenja, anomalije višjega reda pa so predvsem odvisne od mikroreliefa stične površine. Priporočeni so ukrepi za doseganje homogene deformacije pri plastometričnih preizkusih. Ti kažejo, da deformacija reološko kompleksnih materialov poteka po zakonih, ki se razlikujejo od sodobnega razumevanja mehanizma plastične deformacije.
Ključne besede: plastična deformacija, reologija, deformacijske anomalije, kontaktno trenje, homogena deformacija.

1. Introduction

The development of new technologies of pressure shaping depends on the knowledge of rheological properties of the plastically deformed material. The dependence between the resistance to deformation σ and the deformation rate ϵ at different strain rates σ and temperatures T is a family of curves σ-ϵ, it is specific for each steel and alloy and it is a rheological passport of the material. The most reliable are rheological curves obtained by compression tests on cam plastometer **(fig. 1)** at constant strain rates (1). The condition σ = const is ensured by the cam profile which is given by the logarithmic law

$$\frac{h_0}{h_0 - \Delta h} = \exp\left(\frac{\varepsilon}{\upsilon}.x\right),$$

with h_0 – initial height of the cylindrical specimen 4;
Δh – absolute cogging of the specimen all over its height;
υ – circumferential speed of the drum 1;
x – length of the cam profiled part 2.

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The ensurance of the specimen deformation homogeneity (2), thus the elimination of barrel formation, twisting, shift, bending and other deformation anomalies is the basic requirement in plastometric tests.

It is generally accepted that contact friction forces only influence the deformation of the specimen during its plastic compression. The present investigations refute this point of view and show experimentally that the development of deformation anomalies depends to a great extent upon the rheological complexity of the deformed metal.

2. Rheology of the investigated material

Non-strengthenable materials of the first rheological class and monotonously strengthenable materials of the second rheological class are regarded as rheological simple (3). Rheological complex materials differ from them by presence of extrema on the σ-ϵ curves.

In this work steels and alloys with one maximum on σ-ϵ curves are examined which belong to the most widespead third rheological class (4) of metallic materials with the characteris-

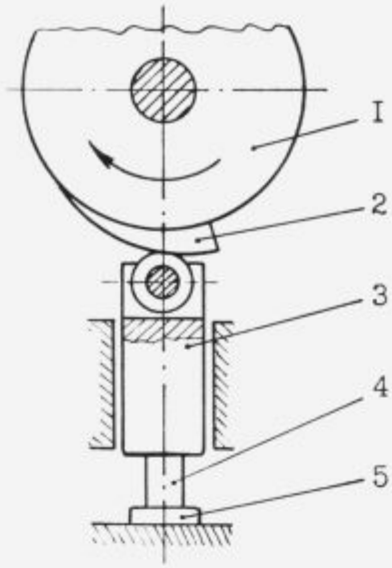

Figure 1: Scheme of cam plastometer: 1 - drum; 2 - profiled cam; 3 - plunger; 4 - specimen; 5 - force-measuring element.

Slika 1: Shema tlačnega (cam) plastometra: 1 - valj, 2 - profiliran nastavek, 3 - bat, 4 - preizkušanec, 5 - merilnik sile.

tic deformation σ_s at the maximum of resistance to deformation σ_{max} (5). The smaller is the value σ_s within the limits of the rheological class, the higher is the degree of the material rheological complexity. In **fig. 2** rheological curves of carbon steel (a) with a characteristic degree of deformation σ_s = 0.4...0.6 (6), high-speed alloy steel (B) with σ_s = 0.3...0.4 (7), and as unique for it degree of rheological complexity (C) a zirconium alloy (8) are shown. The characteristic degree of deformation of the cirkonium 2.5% Nb alloy is only σ_s = 0.03...0.05 and its rheological curves could be better qualified as "curves of unstrengthening" than as "curves of strengthening". The deformation of such materials occurs according to laws which are different in principle of the modern conception of the mechanics of material plastic deformation. The close study of the development of deformation anomalies of higher order (4) of rheologically complex materials would probably promote the development of the theory and technology of metal pressure shaping.

Easily deformed lead alloys-models of different rheological complexity were developed for the modelling new processes of metal pressure shaping at the Ukrainian Metallurgical Academy. **Fig. 3** shows some σ-ϵ curves for a technically pure lead (99.98% Pb, curve A) and alloys with 99.9% Pb (curve B), 99.4% Pb (curve C) and 99.0% Pb (curve D) obtained by cam plastometric tests in compression at the temperature of 15°C and strain rate σ=0.3 s^{-1}. If pure lead is qualified as a second order rheological monotonously strengthenable material ("A") then, depending on the content of additions, the alloys have a maximum on curves σ-ϵ, which shifts to a smaller deformation degree, from σ_{sh} = 0.63 to σ_{sd} = 0.23, which complicates their rheology.

It should be noted that earlier the rheological (but not deformational) complexity of lead was observed either at high temperatures (9) or by static loading (10) what made it unsuitable for the use in physical quantitative modelling of the pressure shaping processes based on the similarity theory.

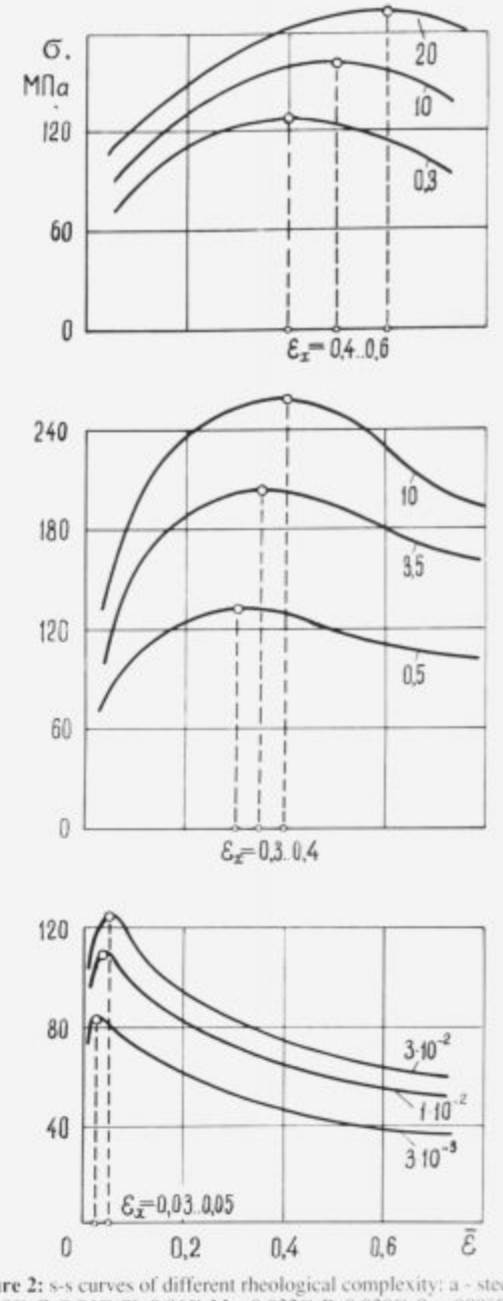

Figure 2: s-s curves of different rheological complexity: a - steel with 0.19% C; 0.04% Si; 0.86% Mn; 0.022% P; 0.029% S at 900°C (6); b - high speed steel with 0.88% C; 0.39% Si; 0.23% Mn; 0.03% P; 0.011% S; 3.3% Cr; 6.39% W; 4.72% Mo; 2.23% V at 1100°C (7); c - zirconium alloy with 2.5% niobium at 775°C. (8) all at the indicated values of strain rate in s-1.

Slika 2: s-s krivulje z različno stopnjo reološke kompleksnosti: a - jeklo z 0.19% C; 0.04% Si; 0.86% Mn; 0.022% P in 0.029% S pri 900°C (6); b - hitrorezno jeklo z 0.88% C; 0.39% Si; 0.23% Mn; 0.03% P; 0.011% S; 3.3% Cr; 6.39% W; 4.72% Mo in 2.23% V pri 1100°C (7); c - cirkonijeva zlitina z 2.5% Nb pri 775°C. (8) vse pri označeni deformacijski hitrosti v s-1.

3. Specimens and methods of testing

After vacuum melting and chemical checking the ingots of lead alloys of 50 mm diameter and 10 mm high were pressed into rods of diameter of 5.9 mm and cut into initial blanks of 11.5...11.8 mm of lentgh. In **fig. 4** press mould details used for the calibration of specimens and the simultaneous indentation of a regular microrelief on their butts in form of concentrical trian-

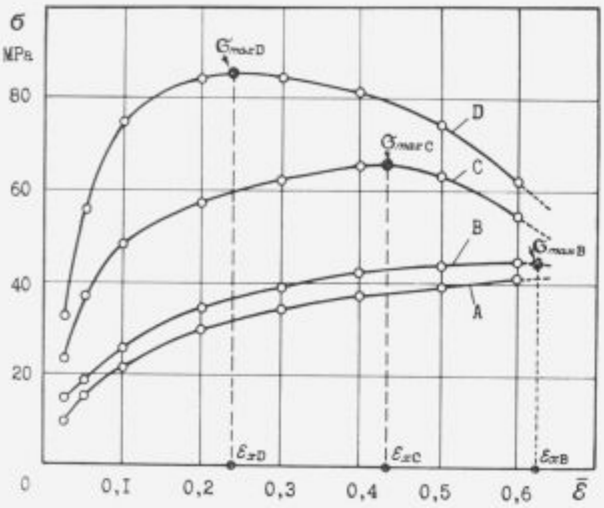

Figure 3: Rheological curves of technically pure lead S1 (99.98% Pb, "A" curve) and alloys of 99.9% ("B" curve), 99.4% ("C" curve) and 99.0% lead ("D" curve).

Slika 3: Reološka krivulja za tehnično čisti svinec S1 (99.98% krivulja A) in zlitine z 99.9% (krivulja B), 99.4% (krivulja C) in 99.0% svinca (krivulja D).

gular juts 0.3 mm high by the plungers 2 and 4 are shown. The final dimensions of the specimen were: diameter - 6.0 mm and height - 11.0 mm. Before the plastometric tests the specimens were annealed at 100°C during an hour and then aged during thirty days at room temperature.

Fig. 5 shows the container for the compression tests of cylindrical specimens. The initial adjustment of the specimen 3 and the plungers 1 and 4 in the container 2 is obtained by means of a simple centring device. Polished working surfaces of plungers and profiled butts of the specimens are covered with layers of viscous lubricant Litol 42 and separated by thin rubber, polyethylene or polyurethane foils. The number of layers of lubricant ensuring the homogeneity of deformation was determined experimentally. If in the process of compression the specimen becomes barrel-shaped, the number of layers is increased, if it becomes concave then their number is diminished.

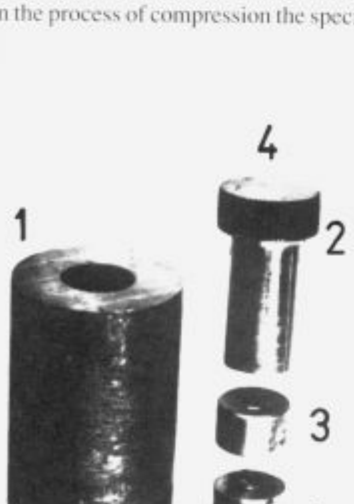

Figure 4: Press mould for pressing and calibration of specimens for plastometric tests: 1 - body; 2 - upper die; 3 - calibrating matrix; 4 - lower die.

Slika 4: Orodje za stiskanje in kalibriranje preizkušancev za plastometrične preizkuse: 1 - ohišje, 2 - zgornja matrica, 3 - kalibracijska matrica, 4 - spodnja matrica.

Figure 5: Container for plastometric tests by compression: 1 - upper die; 2 - body; 3 - specimen; 4 - lower die.

Slika 5: Container za plastometrične tlačne preizkuse: 1 - zgornja matrica, 2 - ohišje, 3 - preizkušanec, 4 - spodnja matrica.

4. The influence of contact friction on the growth of deformation

In case when the radial displacement of metal on the working surface of the plungers is hampered, the butts of the specimens are formed with the contact of it lateral surface and the plunger. **Fig. 6b** shows a pressed pure lead specimen covered with chalk on the initial contact area. The light circle on the butt is the unstrained initial surface, dark circle is a part of the contact area lifted from the lateral surface of the specimen. Also the initial form and the shape after a true homogeneous deformation of the specimen during plastometric tests as a result of the proper lubrication of the contact area are shown in **fig. 6**.

In **fig. 7** specimens of pure lead after sagging at plastometer with strain rate $\sigma = 0.3\ s^{-1}$ by identical parameters, but different conditions of friction on the contact are shown.The specimen 2 was pressed with dry contact surfaces, and a barrel shape was obtained. The specimen 3 was deformed homogeneously as a result of the optimal selection of the lubricant. The concave shape of the specimen 4 which was obtained by increasing the number of layers of lubricant to three with two intermediate rubber separators. In this case the friction force vector changed to the opposite sign and the friction became active in promoting the strong radial displacement of metal adjacent to the contact and the concave lateral surface of the specimen was obtained.

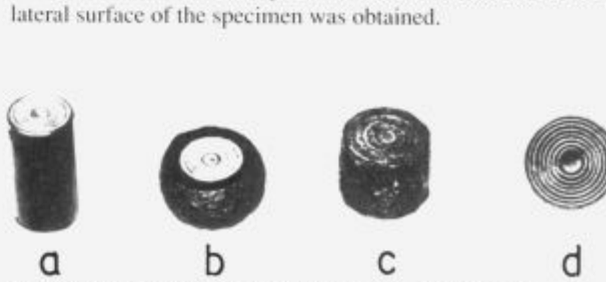

Figure 6: Heterogeneous (b) and homogeneous (c) deformation of pure lead samples S1 (a - initial form of the sample, d - butt relief of the sample).

Slika 6: Heterogena (b) in homogena (c) deformacija preizkušancev iz čistega svinca S1 (a - začetna oblika preizkušanca, d - relief na osnovni ploskvi valjastega preizkušanca).

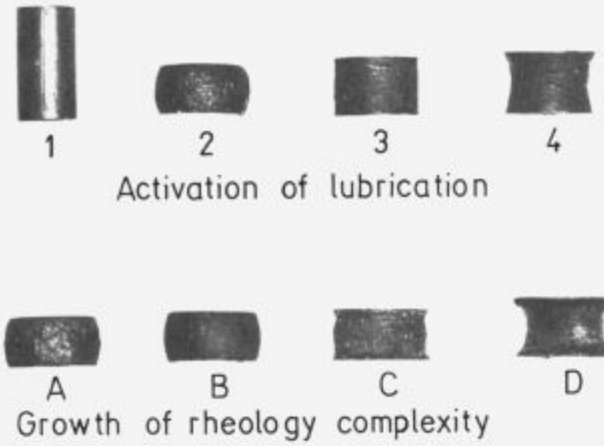

Figure 7: Strain development in pure lead samples by increase of lubrication of butts (2-4) and lead alloys specimens from fig. 3 by different degree of rheological complexity (A-D).

Slika 7: Razvoj deformacije v preizkušancih iz čistega svinca pri povečanem % mazanju stičnih ploskev (2-4) in preizkušancev iz svinčevih zlitin s slike 3 pri različnih stopnjah reološke kompleksnosti (A-D).

Evidently, by plastometric tests of rheologically simple materials the significance of lubricant is very substantial. With modification of the conditions of friction on the contact surfaces it is possible to regulate the development of deformation and achieve its homogeneity.

5. The role of metal rheological complexity in development of deformation

Let us now present some results of plastometric tests of rheologically complex alloys at the same conditions (ϵ=0.6; σ=0.3 s^{-1}) without lubrication.

Fig. 7 (A-D) shows samples of the tested alloys by order of rheological complexity: A - pure lead, B - "B" alloy, C - "C" alloy, D - "D" alloy. As in the previous series of tests the specimen of pure lead (A) is barrel-shaped. The shape of the specimen of alloy "B" with a maximum (σ_{maxb}) on the rheological curve at σ_s = 0.63 (see **fig. 3**) is also barrel shaped. Since only a deformation below σ = 0.63 was achieved the rheological complexity of the alloy did not come to evidence and the specimen was deformed according to the simple strengthenable material of the second class. The specimen of "D" alloy inspite of the sagging without lubrication assumed a quite different shape, a strongly marked concavity of the lateral surface. The rheological curve of the alloy "D" (third rheological class in **fig. 3**) shows that if the deformation is increased above the characteristic value, the resistance to deformation is decreased sharply from σ_{max} = 95 MPa at σ_s=0.23 to 60 MPa at ϵ = 0.6. Simple calculations show that before the deformation has embraced all the specimen volume the triangular juts of it butts did deform to the extent of ϵ = 0.4...0.6. This started a deformation with strengthening of the metal in the bulk volume of specimen and unstrengthening of metal in layers adjacent to the contact. The resistance to deformation of these layers in the very initial stage is smaller and they flow in radial direction with higher speed than the inner layers forming the specimen with concave lateral surface. It should be noted, that in spite of the small depth of the butt relief (0.3 mm) the volume of this unstrengthenable metal is sufficient to initiate the deformation of metal more distant from the contact.

The deformation anomalies in the process of sagging of the alloy "C" (**fig. 7C**) is of special interest. The characteristic degree of deformation of the alloy "C" is achieved by σ_s = 0.43. Up to this moment the adjacent to contact volumes of metal, on account of the greater deformation of the butt microrelief, are strengthened more intensively than those in the depth and the sample becomes barrel-shaped. By further sagging the deformation of metal layers adjacent to the contact above σ_s start to unstrengthen and in the last stage rush intensively in radial direction outstripping the layers in the depth. The specimen acquires a specific shape: concavity near the contact with the tool and barrel-shaping during the final stage of the process. It is concluded, therefore, that the deformation homogeneity must be achieved during all the test.

It is possible to eliminate deformation anomalies of higher orders at plastometric tests of rheological complex alloys by means of greater friction on the contact specimen-tool with the deposition of chalk. Also it can be achieved by selecting the proper specimen butts asperity.

Conclusions

1. The development of deformation anomalies at plastometric tests depends substantially on the degree of metal rheological complexity. Deformation anomalies are caused by inadequate conditions of contact friction while deformation anomalies of higher orders result from the primary deformation of specimen microrelief on the contact with the tool.
2. The homogeneity of deformation at plastometric tests of rheologically complex metals can be achieved by the proper roughness of the specimen surfaces in contact with the tool. Friction at this place either prevents or promotes the radial displacement of the deformed metal.
3. By plastometric tests of metals and alloys it is necessary to control the deformation of the specimen during the whole process in order to reveal and eliminate intermediate deformation anomalies.

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