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Deformation Anomalies of Higher Order during the Plastic Extention of Rheologically Complex Materials

Deformacijske anomalije višje stopnje med plastičnim raztezanjem reološko kompleksnih materialov

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New deformation anomalies of rheologically complex materials were discovered and demonstrated. It was found out that in the process of axial extention during the decrease of resistance to deformation secondary deformation heterogeneities take place alternated with deformation homogeneities due to changes in resistance to deformation.
Key words: rheology, tensile test, deformation, heterogeneities

Odkrite so bile nove deformacijske anomalije reološko kompleksnih materialov in dokazane z raztržnimi preizkusi primernih kovin. Ugotovljeno je, da pri aksialnem raztezanju med zmanjševanjem odpora proti deformaciji prihaja do sekundarnih deformacijskih heterogenosti in homogenosti zaradi sprememb v odpornosti materiala proti deformaciji.
Ključne besede: reologija, raztržni preizkus, deformacija, heterogenosti

1. Introduction

The plasticity is essential for the irreversible change of form of materials and the obtention of a finished product. The measure of plasticity is the extent of deformation energy accumulated in the material up to the failure[1] and it is generally established by testing in conditions of stress-strained state identity. The simplest of such tests is the linear tension or compression of the specimens when the concepts of deformability and plasticity are identic.

Kaibishev defines good plasticity as "high stability" against formation of the neck "at uniaxial extention of the specimen" and explains the possibility of using veritable stress-strain diagrams ∂-ϵ for the estimation of the plasticity[2]. Beside of the uniform elongation and necking the test shows some parameters of the sensitivity of the material to the strengthening rate as well as quantitative data on the plasticity. However the question remains of how to obtain better informations on the materials deformability by means of real stress-strain curves.

Modern metallophysics investigates the separate and combined influence of many factors on plasticity of metals and alloys. For example, on the basis of the analysis of extensive experimental data M. Y. Dzugutov tried to explain why the plasticity of high-alloyed steel decreases and worked out a classification of this multiform phenomenon[3].

However, the complex interrelation between various factors and their influence upon the deformation processes makes the problem of the prediction of the deformability unsolvable without special appropriate experiments. In **ref. 3** the importance of plastometric tests is pointed out, but no suggestion is proposed how to use their results for deformability forecasts.

In literature extensive informations on rheological ∂-ϵ curves obtained by plastometric tests of various metals and alloys are found[4,5]. Their analysis shows that plastically deformed materials can be devided into rheological simple with invariable or strictly increasing function ∂-ϵ and rheologically complex with extreme on ∂-ϵ curves.

Rheological anomalies are well-known and explained. Initial strain anomalies observed as necking of specimens at tensile strain are known too, but the regularities of their development are not fully explored. The influence of test rate and temperature[6], as well as that of the material structure[7] were investigated, however no attempts to study the dependence between the regularities of strain and rheological anomalies were published so far.

This problem was solved by the experimentally discovered and theoretically explained phenomenon of highest order strain anomalies during the tests of rheologically complex materials by plastic stretching.

2. Theoretical analysis

In the phenomenological analysis it is necessary to keep in mind the condition of identity of rheological curves ∂-ϵ obtained by stretching and by compression and the fact that in the integral aspect these curves hold all the information on the changes in the material during the plastic deformation.

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During the tensile tests of unstrengthenable material any casual reduction of specimen cross-section leads to rupture, if it is not compensated by strain hardening and the deformation in form of the necking preceding the rupture. Let's call this well known simple strain heterogeneity "simple strain anomaly".

During tensile tests of strengthenable material the deformation with decreasing cross-section is localised in one section earlier than in others which strengthen because of liquations, favourable orientation of crystallite, etc. and ceases to deform, while other sections of the specimen less strengthened are involved in the flow.

Consequently in the beginning the deformation spreads within the whole volume of the material - we observe the well-known quasi-homogeneous strain of the specimen. According to phenomenological concepts it will be called "homogeneous strain of the first order". The following formation of the neck on the specimen will be called "heterogeneous strain of the first order" or "strain anomaly of the first order".

On the base of the analysis of true ∂-ϵ diagrams and their explanation all materials are classified by the degree of their rheological complexity **(Fig. 1)**.

The first rheological class are simple unstrengthenable materials. By stretching the specimens are deformed according to simple heterogeneous strain with formation of the neck and rupture **(Fig. 1,I)**.

In the second rheological order one finds simple strengthenable materials with a strictly increasing ∂-ϵ function **(Fig. 1,II)**. A typical feature of such materials is the homogeneous strain of the first order, the formation of the neck - strain anomaly of the first order and rupture of the specimen.

The third to fifth classes are rheological complex materials. The third rheological class is charasterized by a maximum on ∂-ϵ curves. The material **(Fig. 1,III)** of this type is stretched through the stage of the first order homogeneous strain, then the neck is formed. The reason is not a lack of plasticity as in second rheological class, but the influence of other mechanisms. The diminution of the resistance to deformation is reached after a limited uniform elongation of the specimen. The process is followed by a considerable decrease of the relative elongation due to the accelerated formation of the neck, however, the value of relative necking is not decreased at the same moment. This anomaly was called "heterogeneous strain anomaly of the second order"[8].

For the fourth rheological class of materials two extreme on ∂-ϵ curve and an subsequent increase of resistance to deformation after the first one **(Fig. 1,IV)** are typical. As in the case of materials of the second class, the extention of the specimen begins with a homogeneous strain of the first order and then, in the materials of the third class, a heterogeneous strain of the second order is observed: the neck starts to form before the elongation ϵt is attained. Here the material reveals its remarkable property: the specimen does not fracture, but it is stretched homogeneously in the region of the already formed neck[9]. The explanation is the secondary increase of the material resistance to deformation in the neck before ϵt **(Fig. 1,IV)**. Outside the process is similar to the homogeneous strain of the first order, embracing only the neck region or, to be more exact, the transition zone from the neck to the main volume of the specimen. This strain anomaly is called according to the proposed terminology as "homogeneous strain of the second order". Many metals (copper, aluminium, lead, etc.) have the remarkable property to restore the plasticity in this way. The further extension of the specimen brings the formation of a localised neck on the earlier elongated neck and causes "a heterogeneous strain anomaly of the third order".

The fifth rheological class of materials is characterized by relations ∂-ϵ with three or more extrema **(Fig. 1,V)**. During the extension the specimen passes through stages of strain typical for the IV rheological class, however without rupture in the localised necks but with further strengthening and uniform elongation due to the homogeneous strain. This anomaly, is called "homogeneous strain of the third order". The following stage is the formation of a new localized neck on the elongated neck of "heterogeneous strain anomaly of the fourth order", and so on.

Multistage strain anomalies of the highest orders on materials of the fifth rheological class are not evident as it is shown schematically in **Fig. 1,V**. The reason are anomaly smooth changes between the different stages and thus the changes are found only by very careful observation.

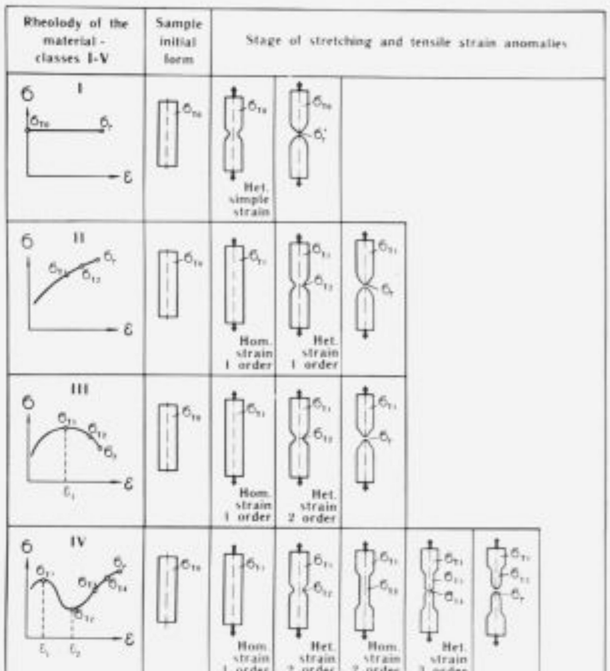

Figure 1: Tensile strain anomalies of materials with different rheology.
Slika 1: Anomalije pri natezni deformaciji materiala

Fig. 2 shows a family of rheological curves for hot-rolled annealed pure titanium (99.9%)[5] which is at 900°C typical representative of an unstrengthenable material of the first rheological class, deformable according to the simple strain heterogeneity type, while at 700°C it is a typical representant of the second rheological class. **Fig. 3a** shows rheological curves for a carbon steel (0.43% C, 0.26% Si, 0.74% Mn, 0.022% P, 0.016% S) representing a very numerous third class of rheologically complex materials. **Fig. 3c** shows ∂-ϵ curves

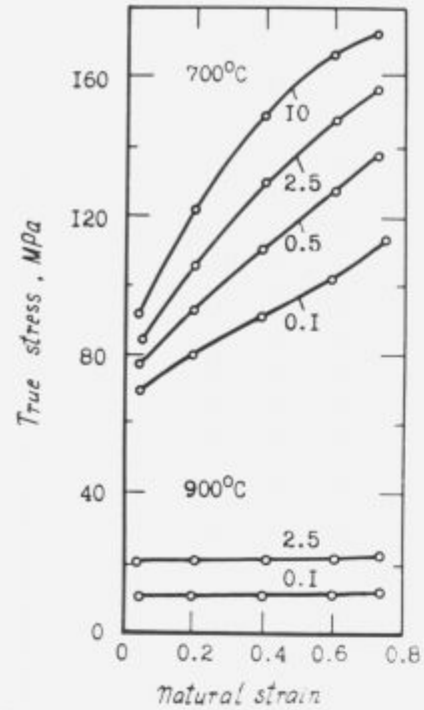

Figure 2: Rheological curves of hot-rolled and annealed Ti (99.9%).
Slika 2: Reološke krivulje toplo valjanega in žarjenega Ti (99.9%).

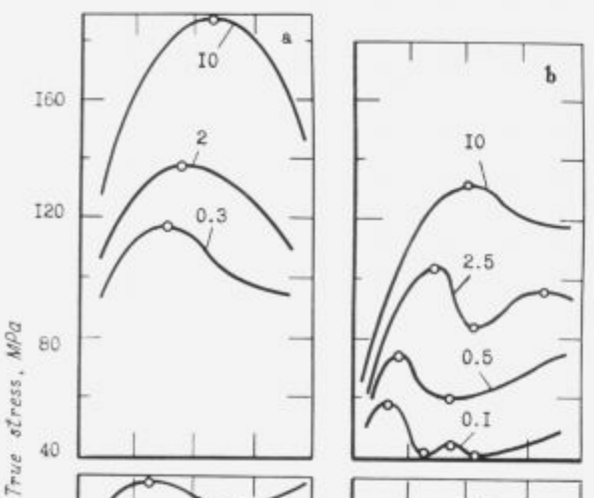

Figure 3: Rheological curves:
a - steel C 45 at 900°C; b - copper (99.99%) at 600°C;
c - aluminium (99.5%) at 480°C6; d - lead C1 (99.98%) at 20°C.
Slika 3: Reološke krivulje:
a - jeklo C 45 pri 900°C; b - baker (99.99%) pri 600°C;
c - aluminij (99.5%) pri 480°C6; d - svinec C1 (99.98%) pri 20°C.

for a technically pure aluminium (99.5%)[7] which is a rheologically complex material of the fourth class with two extrema on the ∂-ϵ curves. Copper (99.99%) is at 600°C[5] a rheologically complex materials of the fifth class with three of more extrema on ∂-ϵ curves **(Fig. 3b)**.

3. Experimental investigations

The experimental investigations of strain anomalies were performed on lead, which has the remarkable property to recrystallize at room temperature **(Fig. 4)**. Processes of its plastic deformation are similar to those during the hot deformation of steels and alloys. It is therefore exceptionally convenient for the modelling[11,12]. The rheological properties of lead are unique. **Fig. 3d** shows rheological curves of lead (99.98%) obtained on a cam plastometer at 18-20°C[13]. At strain rate $\epsilon = 0.005\ s^{-1}$ lead softens completely by recrystallization and it can be thus regarded as a rheologically simple unstrengthenable material of the first class. At the speed of $\epsilon = 0.01$ to $0.1\ s^{-1}$ it has complex relation ∂-ϵ with two extrema inherent to rheologically complex materials of the fourth class. By moderate strain rates (ϵ = 0.1 to 0.5 s^{-1}) lead is a rheologically simple strengthenable material of the second class, while at higher rates it is a rheologically complex material of the third class.

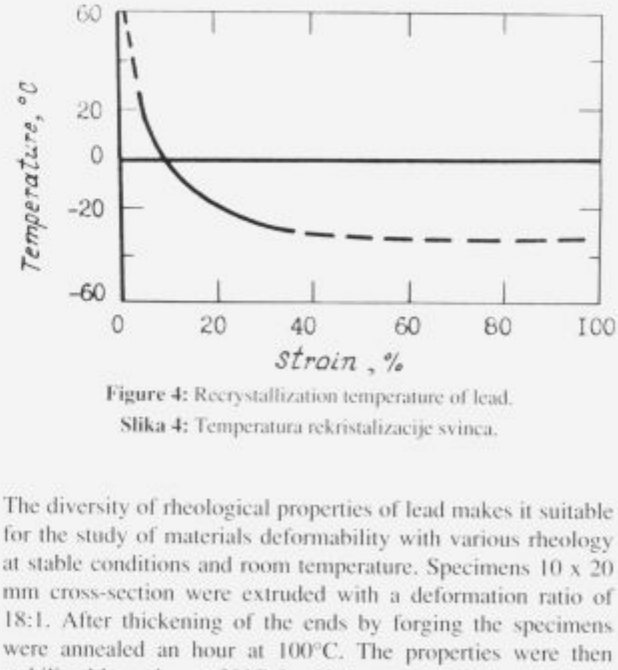

Figure 4: Recrystallization temperature of lead.
Slika 4: Temperatura rekristalizacije svinca.

The diversity of rheological properties of lead makes it suitable for the study of materials deformability with various rheology at stable conditions and room temperature. Specimens 10 x 20 mm cross-section were extruded with a deformation ratio of 18:1. After thickening of the ends by forging the specimens were annealed an hour at 100°C. The properties were then stabilized by aging at 30°C for 60 days and the microstructure was controlled. **Fig. 5** shows the microstructure after annealing and ageing. No grain growth was observed during the thermal treatment. Even slight impurities can change significantly the lead rheology quantitatively as well as qualitatively[13]. In order to have a constant chemical composition the specimens were made of the same melt.

In the analysis of the rheological properties of different metals it was ascertained that at a temperature slightly above the recrystallization temperature the complexity of rheology is revealed more evidently at low strain rates. For this reason the experiments were performed at a temperature of 33-34°C, thus different from the temperature by which the rheological curves

Figure 5: Microstructure of lead.
Slika 5: Mikrostruktura svinca.

∂-ϵ in Fig. 3d were obtained. Investigations were performed on "Fritz Hekkert" FP-10 and FP 100/1 machines at a stretching rates of 0.5; 1; 200 and 1500 mmpm.

It was ascertained that the character of specimen deformation depends at a given rate on the specific rheological relation given by the ∂-ϵ curve from the family of rheological curves in **Fig. 6**.

To ensure an average strain rate of ϵ = 0.004 s^{-1} longer specimens were used (**Fig. 6, specimen No 1**). At this rate lead deformed as materials of the first rheological class with a distinct formation of the neck, thus with a simple strain anomaly. Specimens No 1, No 2 and No 3 were stretched with the same pre-set relative elongation ϵ = 40%.

The average strain rate of specimen No 2 was 0.02 s^{-1} (**Fig. 1, IV**) and a curve of the fourth rheological class was obtained. After a short deformation in the stage of strain homogeneity of the first order the deformation continued by strain heterogeneity of the second order and a local neck was formed. As the extension went on, deformation proceeded according to the secondary homogeneity type. The neck elongated on account of near-by metal volumes and the specimen acquired the shape given in **Fig. 6**, No 2. Though quantitatively rheological anomalies (ϵmax and ϵmin deviations) of lead at this speed are only marked, strain anomalies and differences between them are observed quite distinctly.

Specimen No 3 (200 mmpm) deformed as rheologically simple strengthenable material of the second class in conditions of homogeneous strain.

Specimen No 4 (1500 mmpm) passed a short stage of homogeneous deformation according to heterogeneous strain type and fractured attaining scarcely an elongation of ϵ = 38% while retaining the value of .. = 100% waist. The fall of plasticity is due in this case to the strain anomaly of the second order. At this strain rate rheological curve of lead shows one maximum, which is a characteristic for materials of the third rheological class.

The repetition of experiments confirmed the reliability of the findings. The investigation of strain anomalies of higher orders and the regularity of their occurrence suggest a solution of some interesting problems and reveal the nature of the formation of the strain nidus during the rolling of rheologically complex steels[14].

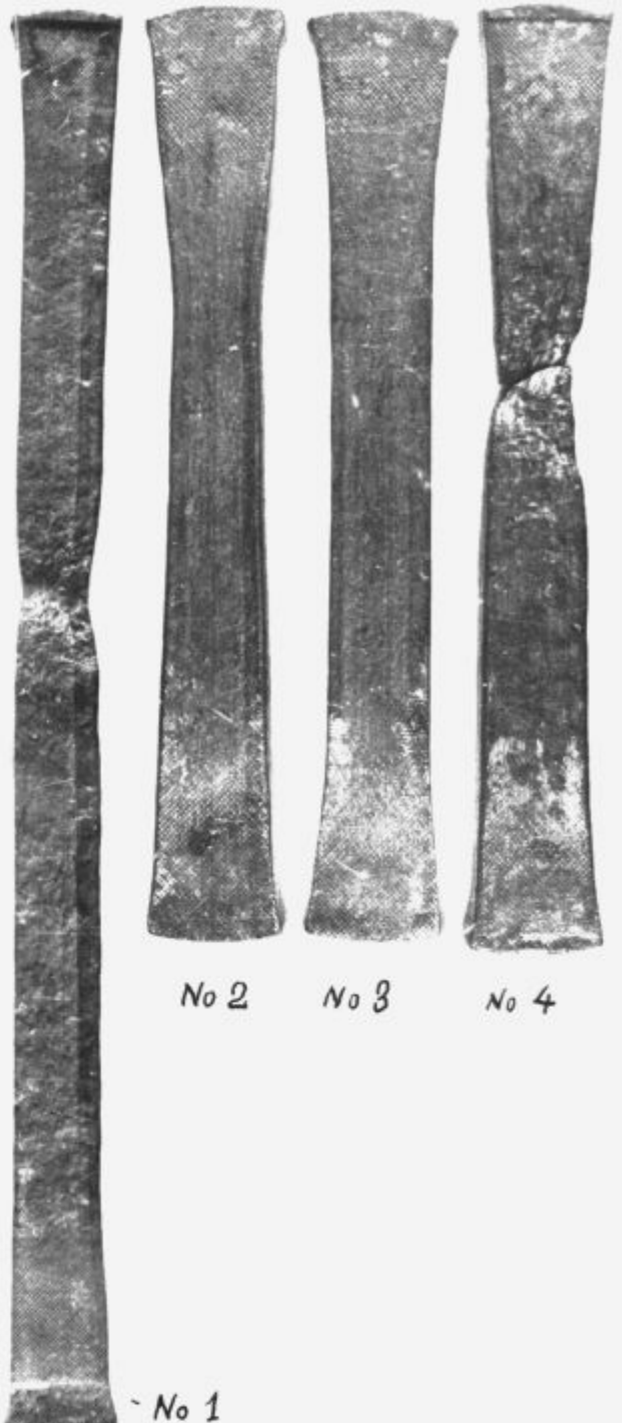

Figure 6: Form of lead specimens stretched at strain rate of mmpm: No 1 - 0.5; No 2 - 1.0; No 3 - 200; No 4 - 1500.

Slika 6: Oblika svinčenih preizkušancev, deformiranih s hitrostjo deformacije: št.1 - 0.5; št.2 - 1.0; št.3 - 200; št.4 - 1500.

4. Conclusion

A phenomenon of strain anomalies of higher orders of rheologically complex materials was determined experimentally and explained. It reveals itself in the process of plastic uniaxial extension, according to the rheological curve ∂-ϵ. Secondary and further strain heterogeneities appear alternated with secondary and following homogeneities which increase the resistance to deformation.

Considering the proposed rheological classification of materials the understanding of regularities of strain anomalies can be used for the solution of theoretical and technological problems connected with the prediction of the development of plastic deformations and of the rupture of rheologically complex materials.

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