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The Rheological Model of Deformation Nidus in the Process of Rolling

Reološki model deformacijskega prostora v procesu valjanja

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On the basis of contemporary ideas on the metal pressure shaping theory and investigation results of the metal stress-strained state during rolling and using variation principles of mechanics, the plastometric classification of metals and alloys, a new rheological model of the high deformation nidus is proposed in this work. The model explains the regularities in the distribution of plastic deformation intensity in the non-contact zones as well as the formation of the feed front end deformation in dependence of the plastometric properties of metals. Experimental data confirming the validity of the model are given also.

Key words: rolling, plastometry, rheology, deformation, straining, deformation nidus.

Na osnovi sodobnih pogledov o teoriji oblikovanja kovin, raziskav napetostnega stanja v kovini med valjanjem, z uporabo variacijskih načel mehanike in plastometrične razvrstitve kovin in zlitin, se predlaga nov reološki model visoko deformiranega prostora. Ta model razlaga regularnosti v porazdelitvi intenzitete plastične deformacije v coni brez kontakta in nastanek čela deformacijskega prehitevanja v odvisnosti od plastometričnih lastnosti kovin. V članku so priloženi eksperimentalni podatki, ki potrjujejo veljavnost modela.

Ključne besede: valjanje, plastometrija, reologija, deformacijska utrditev, deformacijski prostor.

1. Introduction

In spite of the intensive development of mathematical modelling and experimental methods of mechanics, the theory of rolling at present doesn't dispose of reliable informations on the mechanism of building-up of the deformation nidus. Especially little is known on the regularities of metal flow at unstable stages of the process. This may result in the slow development of blooming rolling technology, a low rolling yield and sometimes also in an unsuitable quality of semifabricate.

The plastometrical (rheological) properties of metals play a very important role in the formation of the deformation nidus. The influence of rheology on the development of regularities of deformation at rolling of rheologically complex materials is especially important by extremes on σ - ϵ curves. In references **1** and **2** the higher order deformation anomalies during the testing of rheologically complex materials by means of plastic tensional are described. The necking of the sample with the decrease of resistance to deformation ($d\sigma/d\epsilon<0$) on the σ - ϵ curve represents the secondary deformation heterogeneity. With increased resistance to deformation, according to the σ - ϵ curve, a second secondary deformation homogeneity appears in form of uniform elongation of the neck. Thus, changes on the $d\sigma/d\epsilon$ curve are alternated by anomalies in deformation gradient and intensity. This is the base for the proposed rheological classification of materials shown in **fig. 1** and established on the basis of experimental data: I class- simple unstrengthenable materials; II class- simple strengthenable materials; III-V classes – complex strengthenable materials.

The experimental investigation of the deformation nidus stress strained state was realised considering the requirements of the similarity theory **(3)** and using a laboratory device **(4)**. It was necessary to reveal the mechanism of the formation of the knurl on the ends of rollings-a wide-spread defect on blooming rolling **(fig. 2)**.

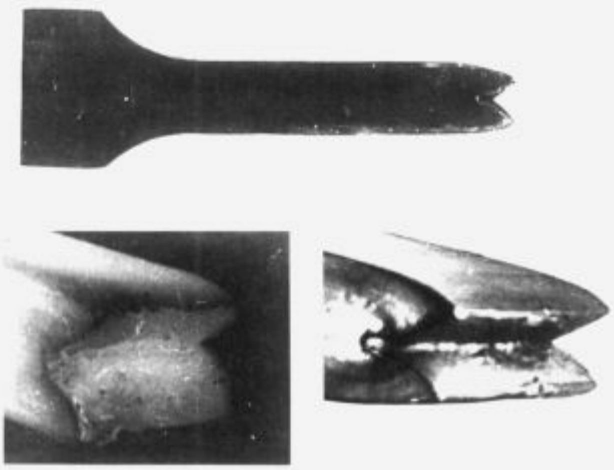

Figure 2: Widely spread defect: knurl on the front end of the rolling: **a**-general view; **b**-during rolling on the blooming "1300" at 1150°-1200°C; **c**-laboratory model of knurling.

Slika 2: Zelo razširjena napaka: odprta ustnica in čelo valjanca: **a**-splošen pogled; **b**-po valjanju na blumingu "1300" pri 1150°C-1200°C; **c**-laboratorijski model ustničenja

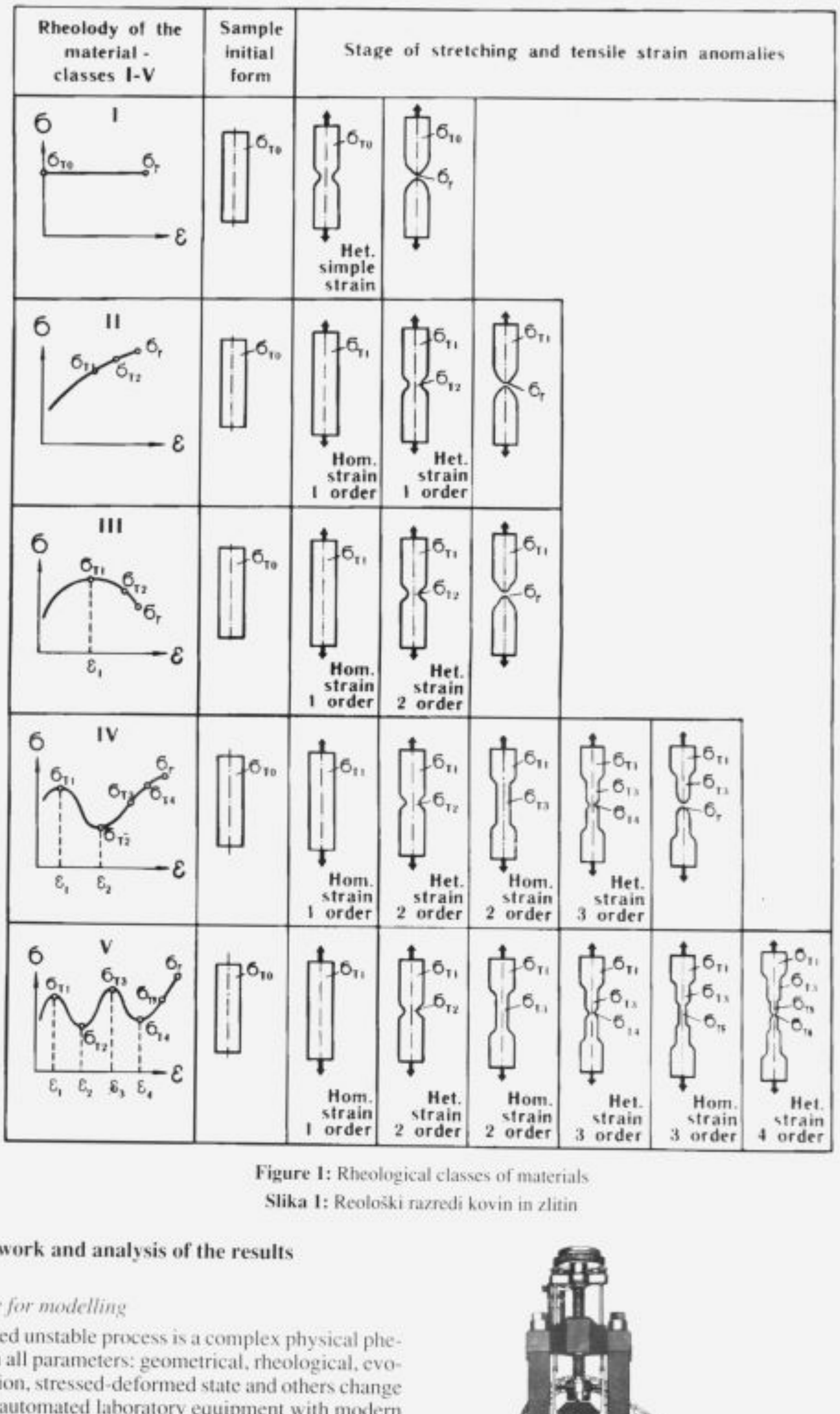

Figure 1: Rheological classes of materials

Slika 1: Reološki razredi kovin in zlitin

2. Experimental work and analysis of the results

Laboratory device for modelling

The investigated unstable process is a complex physical phenomenon in which all parameters: geometrical, rheological, evolution of deformation, stressed-deformed state and others change in time. A special automated laboratory equipment with modern measuring instruments was build for the modelling of this process considering the similarity criteria. The base of this device is a new rolling mill without spindles **(fig. 3)** - a model of blooming **(5)**, with roll diameter of 80...200 mm and length of 120 mm, and a rolling force of 0,3 MN. The main drive is a direct-current motor of 1,5 kW. The circumferential speed of rolls varies within the ranges of 0-100 mmph and of 2-50 mmps. On the device it is possible to obtain an unfinished rolling (an instantaneous deformation nidus) by means of "shooting off" the upper roll at a determined moment and use modern investigation

Figure 3: General view of the new laboratory rolling mill

Slika 3: Splošen pogled na novo laboratorijsko valjarno methods such as moire, photoelasticity, filming and strain measurement to measure the integral characteristics of the process (efforts, moments, displacements and others).

The laboratory equipment includes also auxiliary devices for the preparation and realization of the trial: presses, stamps, tensometric and optical instruments, etc. All parts of the device are unified in an integrated system with an automatic programmed control which ensures the precision and quality of the tests.

The rheological model

Lead-a natural model of hot steels and alloys, has the remarcable property of recrystallization at room temperature. It deforms at low efforts, it is brazed reliably after grating using the moire method and has a perfect plasticity.

A careful study of its rheology shows one more lead property **(fig. 4)**. At various strain rates shows plastometric curves of different rheological classes, from simple unstrengthenable I class (at $\epsilon<0{,}01$ s^{-1}) and strengthenable II class (at $\epsilon = 1...13{,}5$ s^{-1}) to complex strengthenable III class (at $\epsilon = 13{,}5...60$ s^{-1}) and IV class ($\epsilon = 0{,}01$ s^{-1}).

This behavior makes it possible to use lead and its alloys as rheological models for different steels and alloys. Earlier investigations **(6)** showed that its use makes it possible to respect strictly the similarity criteria in the modeling of rolling processes on rolls of optical and organic glass by means of photoelastic observations. Technically pure lead (99,98% Pb) was used in this work.

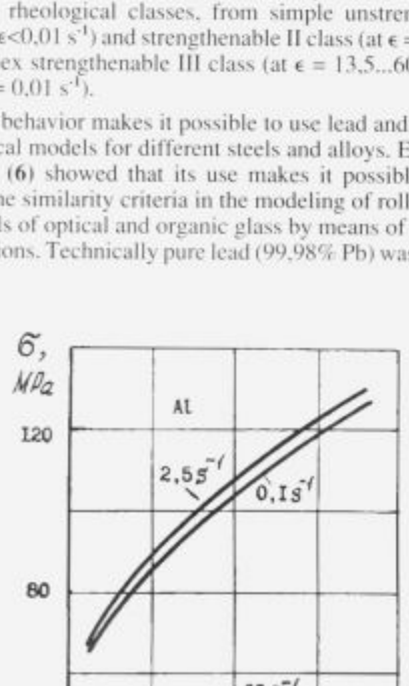

Figure 4: Plastometric curves Pb (99,98%) and Al (99,7%) at 20°C

Slika 4: Plastometrične krivulje za 99,98% Pb in za 99,7% Al pri 20°C

Nuclea of maximum strain rates during the rolling

Experimental investigations of the mechanism of the formation of the deformation nidus were performed after a theoretical and experimental analysis of the metal stress-strained state. **Fig. 5a** shows the intensity field of strain rates H(x,y) obtained by solution of the variation problem using the methods proposed in **ref. 7**. **Fig. 5b** shows the experimental data for a stable process of rolling obtained by the moire method. **Fig. 5c** shows the field of strain rates $\epsilon(x,y)$ at the initial stage of cogging of the slab edges by edging rolls obtained by mathematical simulation using the method of finite elements **(8)**.

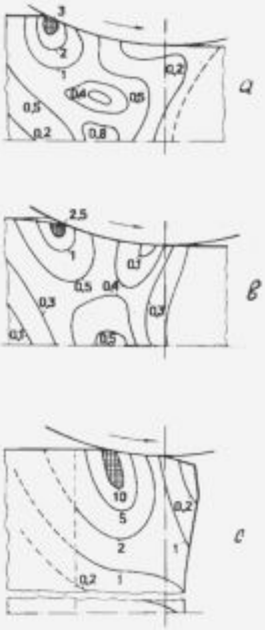

Figure 5: The field of strain rates in s^{-1} obtained by the methods of: **a**-finite differences **(7)**; **b**-moire patterns and **c**-finite elements **(8)**

Slika 5: Polje deformacijskih hitrosti v s^{-1} izračunano po metodah: **a**-končne razlike **(7)**; **b**-moire figure in **c**-končni elementi **(8)**

Though the methods were different, their results agree well and show several common features of the deformed state in the deformation nidus: 1-high heterogeneity of the deformation; 2-extension of plastic regions far beyond the geometrical limits of the deformation nidus, and the presence of the nuclea with maximum intensity of strain rates H_{max} (hatched regions). The H_{max} nuclea on **fig.5a** ($H_{max} = 3$ s^{-1}) and **fig. 5b** ($H_{max} = 2{,}5$ s^{-1}) are located in the initial contact regions at the very beginning of the deformation nidus.

An important conclusion can be derived from these results, the location of H_{max} nuclea does not depend on the degree of metal fullness of the deformation nidus **(see fig. 5c)**.

Mechanism of the formation of the knurl

The unstrengthenable metal through the regions of strain rates maximum intensity (H_{max} nuclea) strives the flow towards the nearest free surface-towards the front end of the rolled piece. From the H_{max} nucleus, as the source, it strives forward in direction of the rolling, overtaking the roll surface and the central part of the metal. This is how the knurl is formed **(fig. 6a)**.

In case of rolling of strengthenable metal the size of the knurl depends on the strain hardening degree. This hardening grows adjacent, to contact layers and reaches in the nucleus a H_{max} sufficient to deplace the stretching to deeper layers of the metal down to the center. Central layers rush forward and flatten the front edge of the rolled piece up to the complete elimination of the knurl **(6b,c)**. Thus, the extension of strain in the front end of the rolled piece is determined by the rheological properties of the metal. During the hot rolling alternated by softeming and recrystallization phenomena the rolling speed plays and important role. At low speed the to H_{max} strengthened nucleus has the time to soften. This explains the formation of the knurl while at high rolling speed and the virtual absence of softening the knurl is not formed.

Pictures of the samples in **fig. 6a** were obtained at different stages of the formation of the strain nidus and before the stabilisation of the rolling process. The rolling was performed in the high-speed regime of the third rheological class, when the additional softening, which causes a strain heterogeneity of the second order, occurs in the H_{max} nucleus. The layers adjacent to the contact surface do not soften not only because of shortage of time, but also because of the $d\sigma/d\epsilon<0$ rheological anomaly. Sliding on the roll the metal in these layers is literally extruded from the strain nidus twisting towards the centre of the sample, and the formation of the knurl is intensified to the maximum.

During the rolling of lead in the regime of the second rheological class ($\epsilon = 1...1.5\ s^{-1}$) the adjacent to contact layer of the metal has no time to soften and that prevents the formation of the knurl **(fig. 6b)**.

Several experiments under the same conditions, but with different rolling speeds were performed additionally on alluminium with the aim to check the reliability of the explained mechanism. The plastometric characteristic of alluminium shows that it is a material of the second rheological class with strictly increasing function σ - ϵ **(see fig. 4)**. In the deformation nidus it practically does not soften at room temperature. Thus the metal adjacent to the contact surface, strengthened by the passage of H_{max} nuclea **(see fig. 5)**, is not elongated in the direction of the exit from the rolls and deeper layers of the metal are deformed. If at the first moment the adjacent to the contact layer of alluminium, which had no time to strengthen, outpaces the central area then, because of the strengthening, their deformation is delayed, while the central area is rushed forward outpacing the adjacent to the contact layers and prevents the formation of the knurl **(see fig. 6c)**.

Thus, the mechanism of the formation of the strain nidus during the rolling is determined by the degree of metal rheological complexity.

The plants producing rolled carbon steels lose a considerable quantity of metal because of the cuttings. During the blooming rolling the shrinkage cavity is elongated simultaneously with the formation of the knurl and the quantity of rejects is increased. For

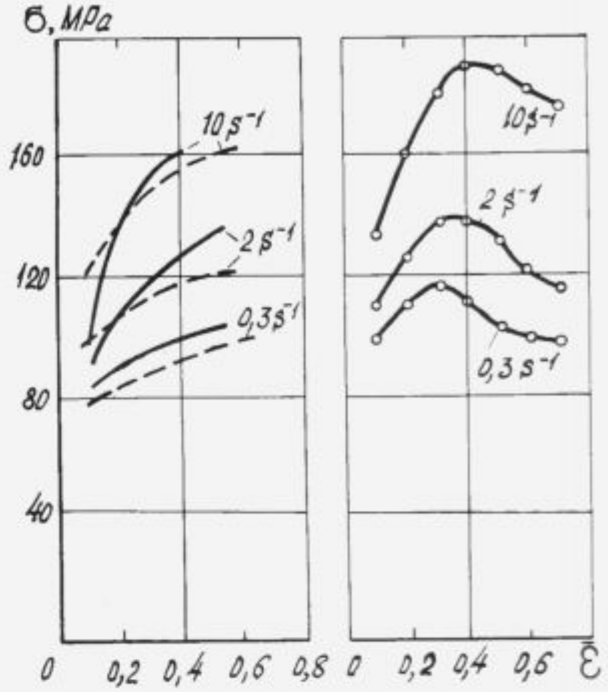

Figure 7: Plastometric curves of carbon steel (0.43% C; 0.26% Si; 0.74% Mn; 0.022% P; 0.016% S) at 900°C: **a**-from **ref. (9)**, **(10)** (dotted line); and **b**-from **ref. (11)**

Slika 7: Plastometrične krivulje za ogljikovo jeklo (0,43% C: 0,26% Si; 0,74% Mn; 0,022% P; 0,016% S) pri 900°C: **a**-iz **ref. (9)**, **(10)** (pikčasta črta); in **b**-iz **ref. (11)**

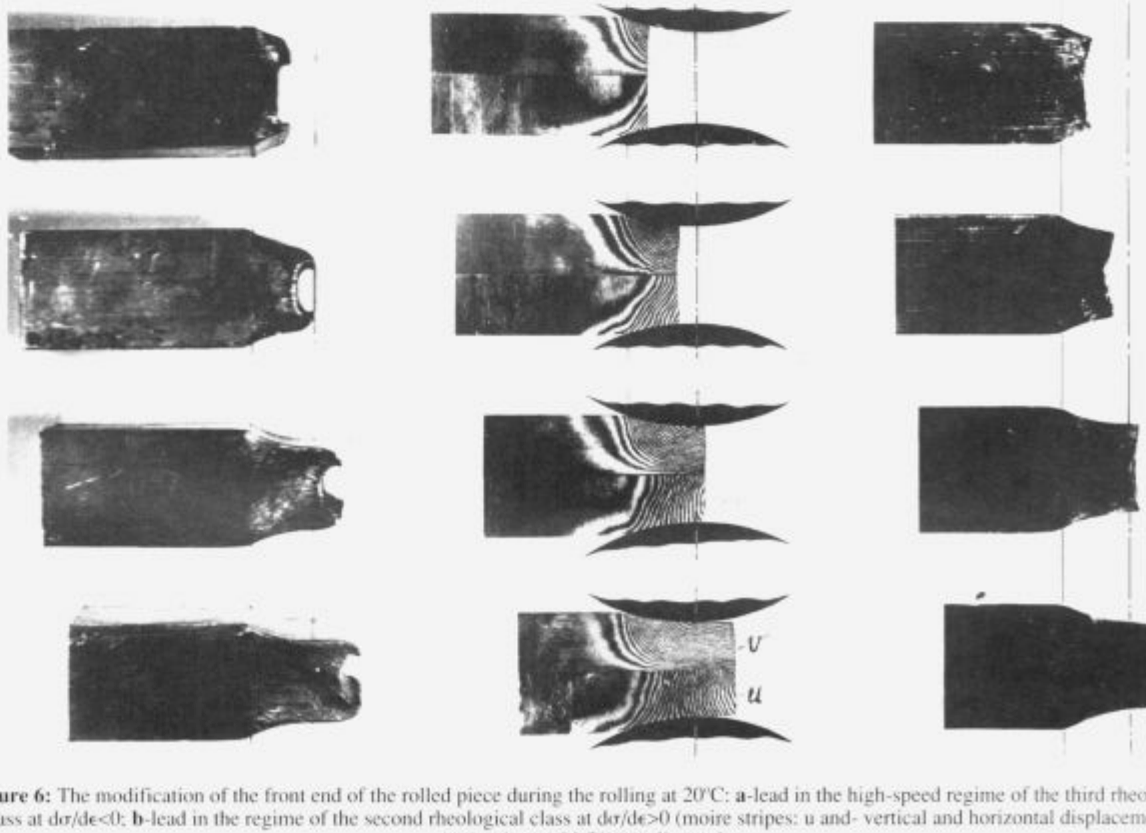

Figure 6: The modification of the front end of the rolled piece during the rolling at 20°C: **a**-lead in the high-speed regime of the third rheological class at $d\sigma/d\epsilon<0$; **b**-lead in the regime of the second rheological class at $d\sigma/d\epsilon>0$ (moire stripes: u and- vertical and horizontal displacements); **c**-aluminum (99.7%) at all speeds

Slika 6: Sprememba čela valjanca med valjanjem pri 20°C: **a**-svinec pri velikohitrostnem režimu tretjega reološkega področja z $d\sigma/d\epsilon<0$; **b**-svinec v režimu drugega reološkega področja $d\sigma/d\epsilon>0$ (moire pasovi, u in v - navpični in vodoravni premiki); **c**-99,7% Al pri vseh hitrostih that reason the elimination of the knurl with increased speed of gripping during blooming rolling of carbon steel ingots (0.43% C; 0.26% Si; 0.74% Mn; 0.22% P; 0.016% S) was checked. It failed because of the rheological properties of the steel **(fig. 7)**. The plastometric curves from **ref.** |**9**| and |**10**| were used under assumption that the steel was rheologically simple and of the second class **(see fig. 7a)**. In reality, according to the investigations of Suzuki, it is complex **(fig. 7b)** and of the third rheological class |**11**|. The reason for the knurling were the deformation anomalies of the second order at d|/d|<0. A diminution of the knurling could be obtained only by means of decrease of the deformation degree (in H_{max} nucleus).

The analysis of the rheology of carbon steels (0.2 - 1.0% C) according to Suzuki showed that these steels were rheologically complex of the third class with the maxima on σ - ϵ curves at all strain rates and temperatures. That means that the propensity to deformation anomalies is inherent to these steels. The formation of the knurl is inevitable and the only way to diminish it remains the change of the rolling regimes or of the form of the ingots.

Formation of the prenidus plastic zone

Fig. 8 shows the results of several experiments performed with the aim to explore the development of deformation in the prenidus zone by modelling on the laboratory rolling mill. Samples-ingots 40x40x200 mm prepared with high accuracy from preliminarly pressed and with stabilized properties (annealing one hour at 100°C and ageing at 25°C during 60 days) lead (99.98% Pb) were rolled with 80 mm rolls with a deformation $\epsilon = 25\%$.

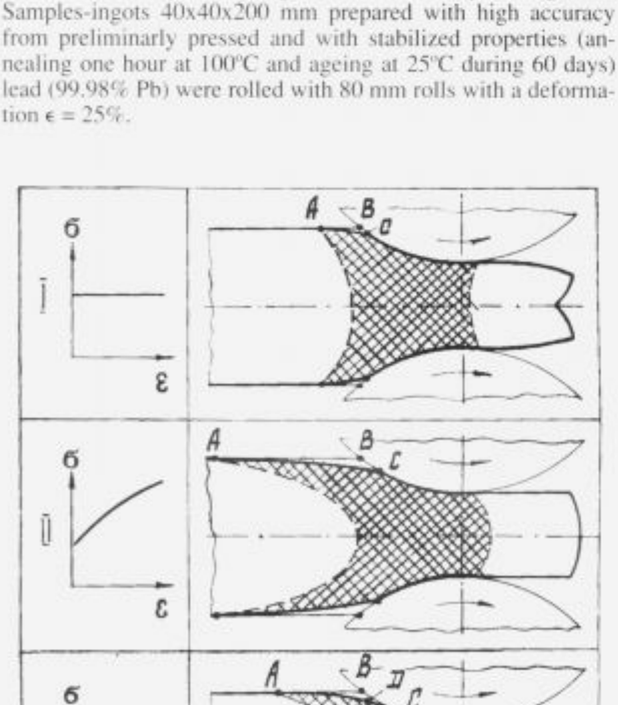

Figure 8: The shape of the deformation nidus during the rolling of metals with different rheology

Slika 8: Oblika deformacijskega prostora med valjenjem jekel z različno reologijo

The extension of the prenidus plastic region was determined by means of moire stripes and indicator devices operating with the error of ±0.01 mm. Differences in rheology of the deformed material were achieved by change of strain rates in the range of $\epsilon = 0.0005$., 0.01 and 1.5 s^{-1}.

During the rolling in regime of simple unstrengthenable first class the prenidus deformation was maximal **(see fig. 8, I, AB)**. During rolling in the regime of the second rheological class (with maximum strengthening) the extension of the prenidus plastic zone was maximal. Strain homogeneity of the first order promotes the inclusion of layers of metal more distant from the rolls into the deformation. These materials are optimal from the rolling technology stand point.

The processes of the development of the second order strain heterogeneity were observed during the rolling of the material of the third rheological class with a maximum on the σ - ϵ curve **(see fig. 8, III, AC)**. The extension of the zone of non-contact deformation in front of the rolls was smaller than in the previous case and the displacement of "C" point-the beginning of contact of the metal with the rolls, towards the line of roll centres was observed constantly. This could produce a strain heterogeneity of the second order with elongation of the surface layers joining points "D" and "C" in an avalanche and could lead to the destruction of metal, especially when concentrators of stresses in form of defects are present.

3. Conclusions

A new model for the formation of the plastic deformation nidus during the rolling was developed using a rheological classification of metals based on experimental data:

1. It is shown, that the strained state of metal in the nidus of deformation is characterized by the presence of regions with maximum strain rates - H_{max} nuclea and depends substantially on the rheology of the metal.
2. The mechanism of formation of the widely spread defect-knurl on the ends of the rolled pieces is explained. It was ascertained that the formation of the knurl depends on the rheology of the metal and the rolling speed.
3. Regularities of the formation of the non-contact prenidus zone of plastic deformation were ascertained.
4. Rheological σ - ϵ data available in scientific literature should be used carefully because in many cases methods of mathematical "smoothing" were used for processing the results of plastometric investigations and rheological anomalies fell-out of the researcher's field of vision.

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