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Influence of Work Hardened Layer Thickness on the Mechanical Properties of Metals

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Problem of metallic material near surface layer plastic yield properties during deformation (monotonic loading, fatigue, creep, wear etc., etc.) has significant theoretical and practical importance. At this time it is determined, that the change of characteristics of plasticity and fracture highly depends on the state of near surface layers, their behaviour and of environment effect. There is also an opinion that any strengthening and fracture theory of metallic material must take into account surface effects. The task of our research was to study the effect of work hardening both on a change of mechanical properties and on the form of monotonous tension diagrams of BCC lattice metals, as well as to define the reasons of these changes.

Keywords: metal mechanical properties, surface layer, monotonic tension, tension diagram, micro-yield, yield plateau, plastic deformation.

1. INTRODUCTION

At present in the literature, there is a great amount of experimental data about influence of various factors on mechanical characteristics of materials. However, the existing physical theories of durability explaining the various phenomena and the experimental facts, often can not be related one to other both qualitatively, and quantitatively. It is caused by the circumstance that characteristics of mechanical properties of metal usually are no related to the state of stresses arising in local volumes of metal subjected to deformation [1 – 4].

Anisotropy of physico-mechanical properties is to a greater or smaller extent peculiar to all crystalline solids. Recently an interest to studying properties of crystal anisotropy has considerably increased, in particular in case of polycrystals as they inevitably influence on deformation kinetics of solids. There is a close dependence between properties of anisotropy and development of micro-non-uniform deformation of the polycrystalline conglomerate, and, as a consequence, with formation of strength properties of real polycrystalline alloys.

However now still there is no full and clear understanding of character of plastic deformation process in microareas of a polycrystalline alloy. Also, there is disputable question on the beginning of plastic deformation at a monotonic tension.

It should be noticed, that the investigations of heterogeneity of plastic deformation carried out by the majority of authors did not take into account the fact, that deformation in near surface layer and in volume of a material proceeded differently [2 – 6]. Hence, regularities of distribution of non-uniform deformation in microvolumes of a polycrystalline alloy still obviously are not enough investigated. Such investigations are very valuable because the studying of micro-non-uniform plastic deformation regularities will promote formation of understanding of extremely complex picture of strength and plastic properties of a material as a whole.

In case of polycrystalline metallic materials and alloys with BCC lattice the periodical and gradual character of plastic deformation processes at monotonic tension can be presented as follows (Fig. 1) [7].

At the left side of the figure the view of monotonic tension curve, which is observed at temperatures above critical temperature of fragility T_x is shown, and on the right side – at test temperatures lower than T_x. In case of FCC metals and alloys usually on such diagram there is no tooth and yield plateau.

At present in considerations of fracture processes of metallic materials it is accepted to divide all process of strain accumulation and fracture into two basic periods: the period of cracks initiation, and the period of cracks propagation. At monotonic tension, it is possible plastic strain and the damage accumulated up to the beginning of neck formation to classify as the period of cracks initiation, and the neck formation with the subsequent fracture as the period of cracks growth (the shaded area on Fig. 1). Further, we shall consider what basic stages of damage accumulation are peculiar to the period of crack initiation at monotonic loading.

The first stage is the *stage of micro-yield*. This stage lasts from the beginning of the loading until occurrence of the first lines of sliding on the yield plateau. At this stage, such characteristics as a limit of proportionality and a limit of elasticity are determined. In spite of the fact that residual macrostrains at this stage practically equals to zero, the metal microplastic deformation takes place. For metallic materials with a physical yield limit, the ending of this stage is precisely fixed by the beginning of not homogeneous deformation of Liuders – Chernov.

The second stage is the *stage of yield,* characterized by not homogeneous deformation in the form of front Liuders – Chernov passing along all working length of a sample. In the metals with yield plateau at monotonic

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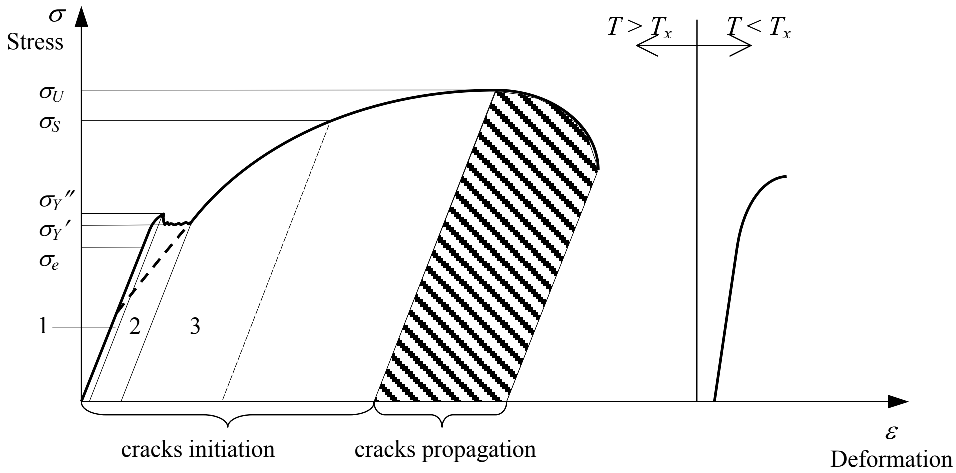

Fig. 1. Failure process stages at static tension BCC lattice possessing metals

tension, heterogeneous deformation on the yield plateau spreads as plastic lava – flow, is related to fast multiplication of dislocations on a line of moving deformation front.

The third stage is the *stage of strain hardening*. At this stage in plastic metals and alloys intensive increase of dislocation density is observed, and at certain critical stress σ_S, on the surface of metal submicrocracks in the size about 1 – 3 μm occur. Inside metal the defective structure in areas with critical density of dislocations also is formed. This stage finishes at the moment, when maximal load is achieved and the neck formation begins.

Achievement of the maximal load on the monotonic tension curve is related to the start of deformation localization and neck formation. The period of cracks growth starts and it lasts from the beginning of neck formation until the final fracture of a specimen.

The described above periodicity and gradual character of fracture at monotonic tension are characteristic for plastic metallic materials. Obviously, that depending on both structural conditions of materials and loading conditions (high and low temperatures, strain rate, an environment) character of the fracture may change, however the general laws of gradual damage accumulation are preserved.

Out of all of these stages at this time the micro-yield and yield stages are least investigated and just they can give the answer to the many still unknown phenomena occurring during deformation.

2. EXPERIMENTAL

The behaviour of near surface layer at all stages of monotonous loading differs from that of internal volumes of a material [2 – 6, 8]. However, complexity of the problem of a role of material superficial area in the general process of plastic deformation is complicated by the influence of many factors relating the actual conditions of near surface layer. The role of near surface layer in change of material mechanical properties is increased, if due to the technological reasons it is exposed to special thermo-mechanical processing, in particular to operations of so-called surface hardening (shot blasting, rolling, diamond ironing, carbon case hardening, nitrogen case hardening, boring etc.). The hardening degree of metals can be evaluated by use of the form of tension diagrams as their form essentially depended on type of a crystal lattice of metal and the previous processing.

It is well known that work hardening essentially influences the strength properties of metals and alloys. Though, the surface hardening has found already wide practical application, however till now there is no full data relating the change of mechanical properties of low carbon steel subjected to various degrees of work hardening. In some cases, this circumstance complicates a choice of optimum regimes of surface hardening, and results in undesirable effects, such like of occurrence the yield of lines at stamping. The task of our research was to study the effect of work hardening both on a change of mechanical properties and on the form of monotonous tension diagrams of BCC lattice metals, as well as to define the reasons of these changes.

Tests were carried out on samples of 35ГC steel of two sets: 1) one of round samples with the length of a deformable part 100 mm, and the diameter – 10 mm; 2) second of plain samples having the length of a deformable part of 65 mm, width – 12 mm and the thickness – 1.5 mm. The chemical composition of 35ГC steel is given in the Table 1.

After machining all the samples were annealed at 850 °C temperature in protective environment. Investigation of samples microstructure has revealed equiaxial grains with an average diameter of 35 μm. The near surface layer of round samples was work hardened with the help of three-roll roller of elastic action, and of plain samples – with two rolls. Monotonous tension of samples was carried out at room temperature at 10 mm/min strain rate. Tension diagrams were recorded by two coordinates self-recording potentiometer, which scale on deformation axis was 10 : 1 and on the force axis was 1 mm – 250 N. In order to investigate the tension diagram in more detail the deformation at micro-yield and yield stages was recorded in scale 65 : 1.

All of round samples and part of plain samples after various degrees of plastic prestrain were subjected to monotonous tension right after work hardening and other part of plain samples - after strain ageing at 100 °C during 3 hours.

Table 1. Chemical composition of 35ГС steel

Material	Chemical composition, %							
	C	Si	Mn	Cr	P	S	Ni	Cu
35ГС	0.35	0.75	0.95	0.30	0.040	0.045	0.30	0.30

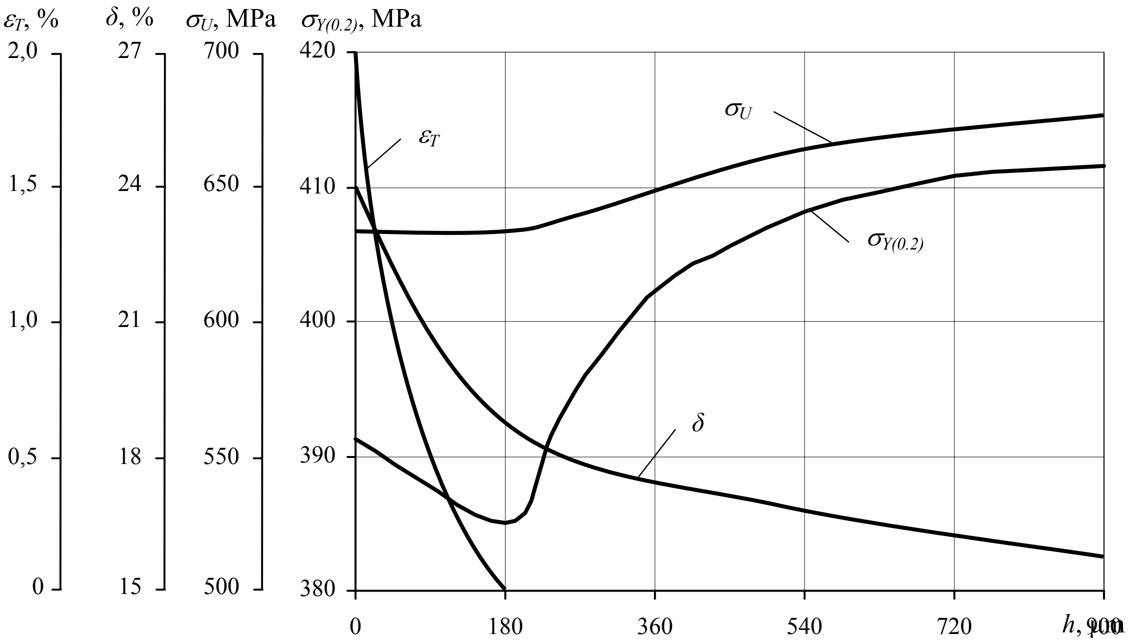

Fig. 2. Influence of the strengthened layer depth (h) on mechanical characteristics of round samples of 35ГС steel

To some of round samples after the surface hardening, the strengthened layer was removed by electrolytic method before the subsequent loading. Chemical composition of the electrolyte: 850 ml H_3PO_4 + 150 ml H_2SO_4 + 50 g CrO_3. The temperature of electrolyte was 20 °C. The big volume of electrolyte (5 litters), continuous mixing and water cooling have provided stability of temperature in the zone of etching in the limits of 1 °C. Such small alteration of the temperature might not activate processes of deformation ageing. The maximum etching duration did not exceed 30 minutes. During this time the natural deformation ageing could not render appreciable influence on strength properties of the metal [9]. The thickness of the work-hardened layer was determined by inductive method [10].

The initial mechanical properties of examined steels, before hardening were determined by monotonous tension of annealed samples. In such way, obtained monotonous tension diagrams were compared to the tension diagrams of the samples, subjected to various degree of work hardening. Fig. 2 presents the data on change of mechanical properties of round samples of 35ГС steel subjected to surface hardening on varying depth.

The figure shows that for the virgin (not work hardened) samples the yield plateau of $\varepsilon_T \approx 2.0$ % lengths is observed. At gradual increase of work hardened near surface layer depth of a sample, the length of yield plateau and yield limit σ_Y decrease, and the ultimate strength σ_U remains not changed. When the depth of work-hardened layer achieves 180 μm, the yield plateau disappears, the yield limit achieves its minimum, and the ultimate strength begins to grow. Further, increase of strengthened near surface layer depth, results that the yield plateau is absent, and the limit of proportionality σ_e and ultimate strength σ_U grow. Besides, the growth of σ_e is more intensive and, at further increase of degree of deformation, the difference between σ_e and σ_U decreases too. Decrease of relative elongation δ with increase of hardened near surface layer depth is small; its high enough value remains even after full disappearance of the yield plateau ($\delta \approx 19$ %).

Form change of monotonous tension diagram of 35ГС steel samples versus the depth of work hardened near surface layer, is shown in Fig. 3. The curve 1 represents not work-hardened sample. The curve 2 represents the sample which hardened layer depth before the tension test equals to 90 μm. It is obvious from the figure, that the initial loading stage of this sample is characterized by lower strain resistance in comparison with that of curve 1. The yield plateau is reduced. The dashed line 3 shows the stress–strain curve of the strengthened by depth up to 180 μm sample. Up to a microscopic yield limit this curve coincides with the curve 1, then goes up according to a dashed line and at the end of yield plateau curve 1 again coincides with it. It is interesting to notice, that the curve 3 corresponds to depth of the work-hardened layer at which the yield plateau disappears, ultimate strength begins to grow, and the yield limit takes minimum value (Fig. 2). At the same time, the yield limit of the curve 3 coincides with a limit of proportionality σpr of the curve 1 (Fig. 3). When traces of plastic strain formed during surface work hardening are distributed on all cross-section of a sample (curve 4) the yield limit strongly grows and the difference between it and ultimate strength decreases. This result strong decrease of relative elongation.

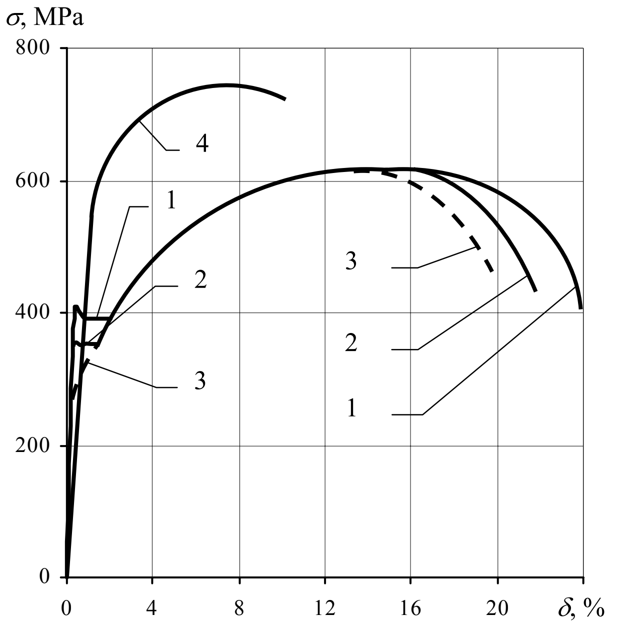

Fig. 3. Change of the tension diagram form depending on the thickness of strengthened layer (*h*) of round samples for 35ГС steel: 1 – an annealed sample; 2 – thickness of the strengthened layer 90 μm; 3 – 180 μm; 4 – the strengthened layer reaches middle of a sample

Aiming to define a degree of near surface layer influence on the character of change of an initial stage of stress–strain curve, from a surface of round samples of 35ГС steel, work hardened to the depth of 90 μm, 180 μm and 220 μm, this strengthened layer was removed by etching. At monotonous tension of these samples, on the diagram the extensive, well-defined yield plateau has appeared. Thus, at full elimination of the effect of surface work hardening, at monotonous tension the samples reveal yield plateau. The fact that the removal of near surface layer results an occurrence of the yield plateau at the subsequent deformation shows that near surface layer plays the important role in plastic yield of metals.

Influence of both squeezing degree ψ and depth of strengthened near surface layer *h* on mechanical properties of plain samples of 35ГС steel is shown on Fig. 4. Analyzing the received data, it may be noticed, that the yield plateau disappears in not aged work hardened samples after squeezing by 1.12 %, and in strain aged samples – after squeezing by 9.6 %. The higher degree of work hardening results initially reduction, and then increase of a yield limit of samples. Ultimate tensile strength of not strain-aged samples initially remains not changed. It starts to increase at the squeezing degree at which the yield strength begins to grow. The growth of ultimate tensile strength of strain aged samples begins at small squeezing degrees. Investigation of the effect prestrain on change of relative elongation δ has shown, that the increase of squeezing degree of strain hardening to samples is accompanied by the higher reduction of relative elongation, than that of samples do not subjected to deformation ageing.

It is important to note, that after skin pass rolling not subjected to ageing the minimum of a yield limit, the increase of ultimate strength and disappearance of a yield plateau observed at squeezing degree by 1.12 %, and the minimum value of yield limit thus coincides with a limit of proportionality σ_e the not strengthened samples. Having in mind, that disappearance of a yield plateau after surface work hardening is related to formation of strengthened near surface layer of the certain thickness, and that the yield plateau occurs again after electrolytic etching of this layer, it may be assumed, that the physical yield limit (parts a, b, c of the diagram in Fig. 5) disappears due to strengthened near surface layer of critical thickness.

At stamping or other kinds of plastic processing of low carbon steel, the sliding strips (lines Liuders – Chernov) appear on its surface. On face side of a sheet of decorative parts formation of sliding strips is completely inadmissible. About the ability of metal to form at stamping yield lines, it is possible to judge from the presence on the tension curve of a yield plateau. The obtained data may be used to exclude sliding strips on the surface of 35ГС steel. This will be achieved if the stamping follows right after work hardening at squeezing degree by 1.12 % and – 9.6 % if the stamping follows the deformation ageing. The results of carried out tests allow to evaluate the effect of a degree and depth of the prestrained layer on strength properties and the type of tension diagram of a carbon steel at room temperature.

Our tests show that at an insignificant squeezing degree (1.12 %) of plain samples and small depth of prestrained near surface layer (180 μm) in round samples, it is possible to remove sharply expressed yield limit and simultaneously to displace the start of the yield to lower stress. Thus surface prestrain results in deformation only near surface layer of the certain thickness. Therefore, the disappearance of a yield plateau after skin pass rolling, apparently, needs to be related to anomalous behaviour of near surface layer of metal subject to tension.

The analysis of causes resulting in reduction of a yield limit and elimination of a yield plateau at small degrees of skin pass rolling should take into account probable Baushinger effect and differences in the mode of prestrain in our experiments and the mode of the subsequent deformation process. In [11] it is shown, that the change of the loading mode reduces resistance to initial movement of dislocations.

The increase of strain hardening depth (for round samples more than 180 μm) results increase of a yield limit σ_Y. This, apparently, is related to the hardening effect prevalence against softening process, which depends on mobility of dislocations at small squeezing degrees. Firstly, the density of dislocations is increased and, consequently, the way of run of mobile dislocations is reduced. Second, by the thickness of strained layer increases and it becomes an effective barrier to an output of dislocations on a

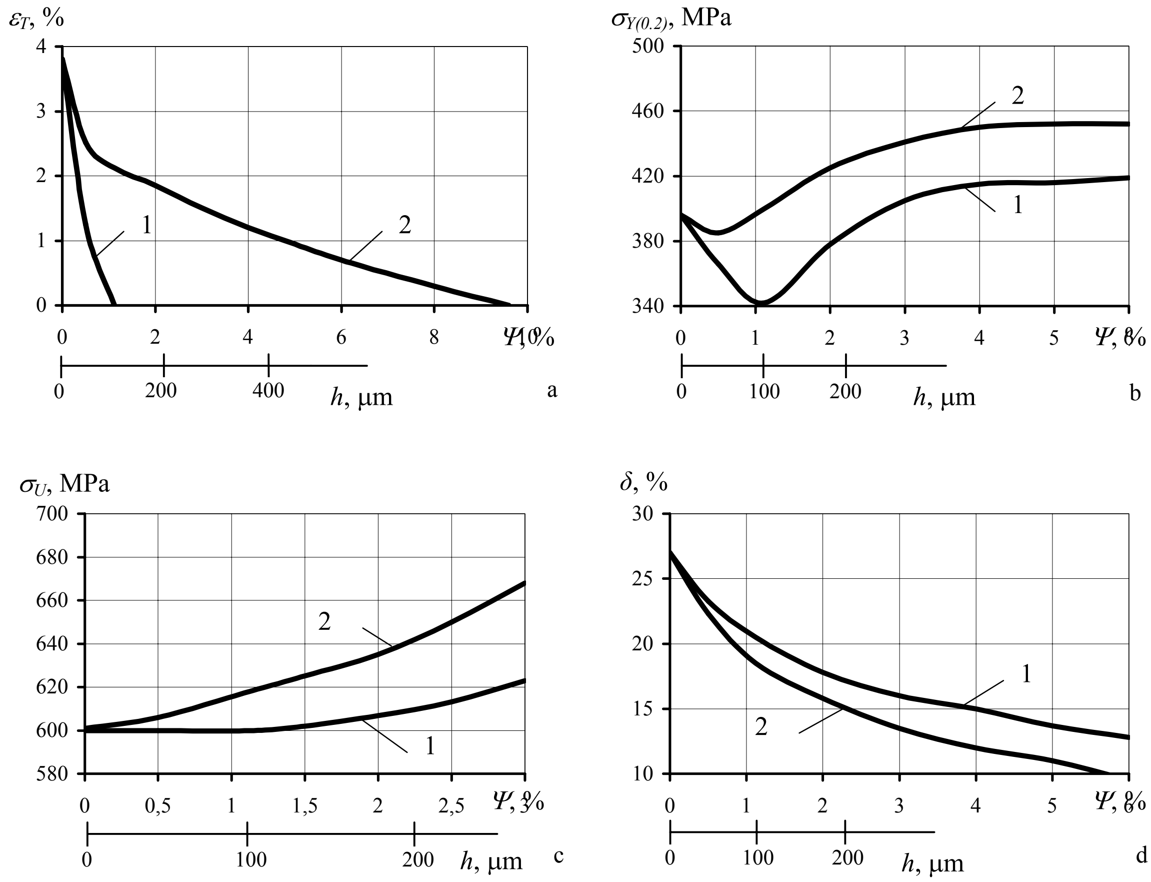

Fig. 4. Influence of squeezing degree (*Ψ*) and the depth of strengthened near surface layer (*h*) on mechanical characteristics of plain samples of 35ГС steel. Samples 1 are subjected to tension right after hardening; samples 2 – after hardening and deformation ageing at 100 °C during 3 hours

surface of metal. Thirdly, Baushinger effect plays less important role, because at a higher prestrain degree quickly achieves "limiting saturation" [11, 12]. These factors at small squeezing degrees are insignificant, however they begin to dominate at the higher degrees of surface work hardening. Direct confirmation of the role of more strengthened and thicker prestrained near surface layer is the increase of the ultimate strength proceeding simultaneously with the beginning of the yield limit increase.

Cold rolling with small squeezing not only gives to a surface desirable smoothness, but also causes lower yield limit, and consequently, easier yield. It eliminates undesirable Liuders – Chernov lines, i.e. improves stamping ability. However, at long storage in cold rolled conditions of sheets the deformation ageing takes place. It causes increase of both yield and endurance limit, formation of a long yield plateau and sliding strips on a sample surface.

It should be noted, that for aged plain samples the physical yield limit stayed unchanged until squeezing by 9.6 % (Fig. 4). At squeezing degrees 2.0 % – 9.6 % the appreciable elongation of all working part of a sample is already observed. However, the degree of deformation near surface layer of metal remains higher. The subsequent ageing fixes this difference of structural conditions, promoting increase of durability near surface layer of metal. Presence in metal of dislocations, mobile at change of a direction of the subsequent deformation, results in reduction of resistance to small plastic deformations that in this case reduce the yield limit (Fig. 4b). The further plastic deformation in the polycrystalline body may proceed as a result of transfer of sliding through

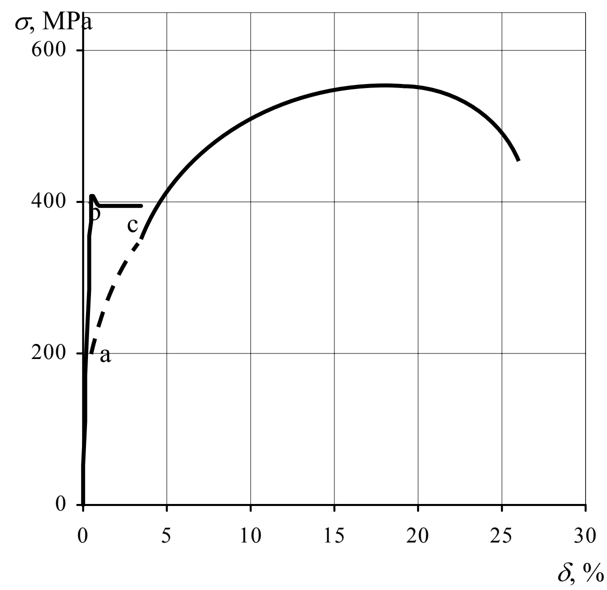

Fig. 5. Tension diagram of annealed plain samples of 35ГС steel

boundaries of grains and overcoming of interaction of dislocations of active system of sliding with a wood of the dislocations lying in crossing planes. This process should be more complicated because crossing planes of sliding during plastic prestrain were active, and, hence, have received the raised density of dislocations, and during the ageing, their fastening by impurity atoms [13] took place. Thus, deformation ageing of the material subjected to surface work hardening, results in more intensive its hardening during the subsequent plastic deformation. Disappearance of a yield plateau and reduction of intensity of yield limit and ultimate strength growth at the big prestrain ratios in part may be influenced by multiplication of dislocations to such high degree that there are no atoms for their fastening.

Thus, investigations show that there is a certain depth of stronger near surface layer at which on monotonic tension curve the yield plateau does not occur. The obtained data qualitatively confirm the idea that presence of a tooth and a yield plateau may be explained by existence of stronger near surface layer of the certain critical thickness [2 – 4, 8, 11].

3. CONCLUSIONS

1. The basic laws of microplastic yield of near surface layers at early stages of deformation of metallic materials and their influence on characteristics of mechanical properties were considered at monotonic loading.
2. The analysis of the obtained experimental data confirms the anomalies of microplastic flow near to a free surface of a solid and its rather essential influence on the general character and kinetics of macroscopic deformation of metals.
3. Work hardening essentially influences the strength properties of metals and the shape of monotonous tension diagram.
4. The hardening degree of metals can be evaluated by use of the form of tension diagrams as their form essentially depended on the previous processing.
5. Cold rolling with small squeezing not only gives to a surface desirable smoothness, but also causes lower yield limit, and consequently, easier yield.

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