

PECULIARITIES OF PLASTIC FLOW OF NEAR SURFACE LAYERS OF CARBON STEEL

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Abstract

At present there is no clear understanding of the character of plastic deformation process in microareas of a polycrystalline alloy. The task of our research was to investigate the character of distribution, magnitude and sign of residual stresses in cross-section of a sample in micro-yield, yield and strain hardening stages of monotonic deformation. The analysis of the obtained experimental data shows the peculiarity of micro-plastic flow near a free surface of a solid body and its rather significant influence on the general character and kinetics of macroscopic deformation of metals.

Key words: near-surface layer, monotonic tension loading, residual stresses, micro-non-uniform deformation, carbon steel

1. INTRODUCTION

Strength problem is particularly important in nowadays technology. Various abundant means are used to achieve this goal. But in whole the world there is a continuous search of the new strength improvement methods and this problem never lose its urgency. At present, in literature there is a great amount of experimental data on the influence of various factors on mechanical characteristics of materials. However, the existing physical theories of durability, explaining different phenomena and experimental facts, often can not be related to one another both qualitatively and quantitatively. It is determined by the fact 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 - 3].

Interest in studying of anisotropic properties of crystal bodies has increased considerably in recent years. There is a close relationship among anisotropic properties, development of micro-non-uniform deformation of the polycrystalline conglomerate, and strength properties of real polycrystalline alloys. Special attention should be paid to studying laws of micro-non-uniform deformation at the earliest stage of the development of plastic deformation [2 - 4].

However, there is no full and clear understanding of the character of plastic deformation process in microareas of a polycrystalline alloy, in particular, it concerns the distribution of deformations in the stage of micro-yield. There is a disputable question regarding the beginning of plastic deformation at a monotonic tension. Hence, regularities of distribution of non-uniform deformation in microvolumes of polycrystalline alloy have not been investigated thoroughly. Such investigations are very valuable because the studying of micro-non-uniform plastic deformation will help to understand a complex picture of strength and plastic properties of a material as a whole [3 - 6].

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 [7] (Figure 1). At present in considerations of fracture processes of metallic materials it is accepted to divide all the 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 propagation.

The first stage is the stage of micro-yield. This stage lasts from the beginning of loading until the occurrence of first lines of sliding on the yield plateau [8]. At this stage, such characteristics as the limit of proportionality and the 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 non homogeneous deformation of Lüders-Chernov.

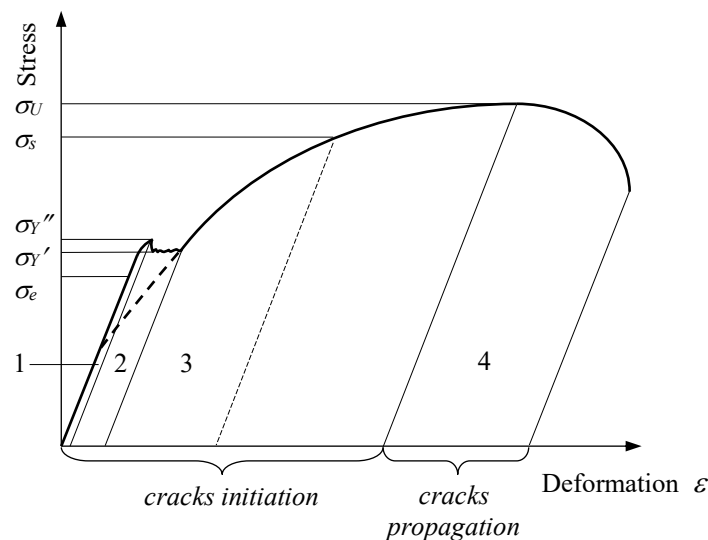


Figure 1. Failure process stages at static loading BCC lattice possessing metals

The second stage is the stage of yield, characterized by non homogeneous deformation in the form of front Lüders-Chernov passing along all working length of a sample. In the metals with yield plateau at monotonic 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 the metal defective structure in the areas with critical density of dislocations also is formed. This stage terminates at the moment, when maximal load is achieved and the neck formation begins.

Stage of cracks propagation (fourth stage) starts from the beginning of neck formation until the final fracture of a specimen.

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

The contradictory data on residual stresses arising in a near-surface layer of a specimen during deformation have still been published in literature [9 - 12]. The task of this research was to investigate the character of distribution, magnitude and sign of residual stresses in cross-section of a sample in all stages of monotonic deformation. It was assumed that if a near-surface layer really has the lowered elastic limit, a plastic deformation will basically proceed in a near-surface layer and this should result in the greatest magnitude of residual stresses in a tested material at unloading. The character of distribution of these stresses allows to judge about the depth of an abnormal near-surface layer.

2. EXPERIMENTAL STUDY

Much attention has been attached recently to the role of residual stresses in determining the properties and behaviours of materials, e.g., strength change, products durability, etc. Residual stresses of the first kind are those that can be continuously measured and recorded in a deflection test of the sample during continuous removal of the strained layers by electrochemical or chemical etching methods. However, such devices are complicated and expensive, and, besides, during the thinning with such devices in most cases gauges continuously contact a sample and thus develop the additional bending moment that distorts the test data.

A device (Figure 2), which with a high degree of accuracy enables to measure the character, size and signs of stresses in a cross-section of laminated samples, was developed.

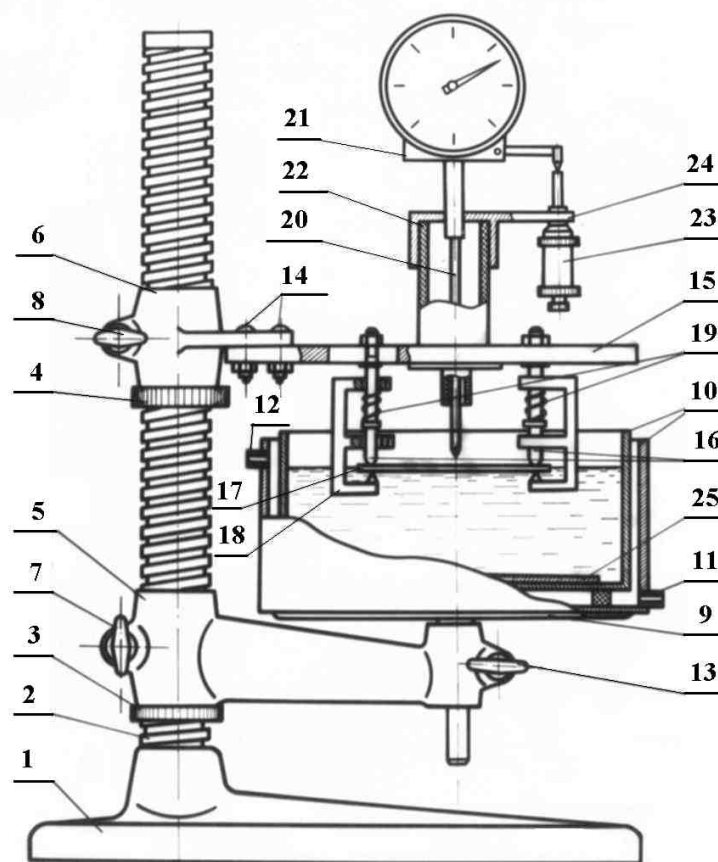


Figure 2. Schematic diagram for a device for determination of residual stresses of the first kind

The device consists of the basis 1, in which the screw 2 is pressed. The rectangular groove of this screw through the nuts 3 and 4 provides free motion of arms 5 and 6 along its axis. The motionless

fastening of the arms is carried out by screws 7 and 8. On the arm 5 the table 9 for the bath with double walls 10 is fixed. In an external wall of a bath 10 the inlet 11 and the outlet branch pipe 12. The table 9 has the axis of rotation fixed by the screw 13. The plate 15 is fastened to the arm 6 by bolts 14. In the guides of the plate two sliding support 16 are mounted. They can be positioned according to the length of a sample 17. The specimen is fixed by clips 18 and springs 19. The leg 20 of the indicator 21 is moved in guides 22 by the micrometric screw 23. The micrometric screw together with the indicator 21 is fastened to the holder 24. During the electrolytic etching the metal sample 17 serves as the anode, and the stainless steel plate 25 of lowered on the bottom of a bath serves as cathode.

This device was used to determine the size and sign of residual stresses of the first kind arising at tension of the near surface layer of a laminated sample. The lateral sides of the sample we used to cover with resistive to acid varnish and clips 18 fixed the sample in the device. The electrolyte filled in the both on 3/4 parts of its volume. The sample was lowered in electrolyte on the depth not exceeding 1/3 part of its thickness. Electrolyte was mixed by specially arranged electric mixer. Measurements of the deflection were made at the given intervals of time corresponding to certain depths of etched layer. They were made in the middle of a sample by means of the indicator 21, which value of division was 1 μm . The contact moment of indicator 21 leg 20 with the sample, aiming to prevent bending of the sample due to the action of the measurement force, was fixed by electric circuit. When the leg 20 touched the surface, the electric contact was caught by headphones and an alarm bulb was lighted. We used to wash a sample together with the device in a bath with water after electrolytic etching was finished.

The thickness of removed layer in process of electrolytic etching was calculated by use of the curve describing the relationship between the time of etching and thickness of a removed layer at constant density of electric current, temperature of etching and electrolyte composition. Then the total thickness

of all removed layers was determined ($\sum_0^N \Delta\delta_N$) by the method of weighing from the relationship

$$\sum_0^N \Delta\delta_N = \frac{\Delta P}{ab\rho} \quad (1)$$

where - δ_N is thickness of N-th etched from surface sample layer; P - loss of weight of a sample as a result of etching; a , b - accordingly length and width of a sample; ρ - density of a material.

Weight of etched material was determined with accuracy of 0.0001 g. The thickness of the removed layers was roughly inspected also with the micrometer. Deflection was measured corresponding to certain depths of the etched layer.

On the basis of the received data the expected value and the sign of residual stresses $\sigma(a)$, acting on the distance a from the top side of a sample, were calculated, according to the relationship [12]:

$$\sigma(a) = [(h-a)^2 \frac{df}{da}(a) - 4(h-a)f(a) + 2 \int_0^a f(\xi) d\xi] \quad (2)$$

where E is the modulus of elasticity of a material; l is the length of a sample; h is sample thickness; f is deflection in the middle of a sample; ξ is distance from the surface of a sample.

Tests were carried out on plain samples of carbon steel with the dimensions of a deformable part $2 \times 16 \times 60$ mm. The chemical composition of this steel is specified in Table 1.

The choice of a material was based on the following reasons. According to the data [13, 14], the increase of carbon contents in a steel (up to 0.8 %) increases the difference between the yield strength of near surface layer and that of all volume of the material (Figure 3). Hence, it may be expected, that in steel with 0.45 % of carbon the difference in behaviour of near surface layers and that of internal layers of metal will be sufficient.

Table 1 - Chemical composition of carbon steel specimens

C	Si	Mn	Cr	P	S	Ni
0.45	0.24	0.60	0.20	0.03	0.03	0.20

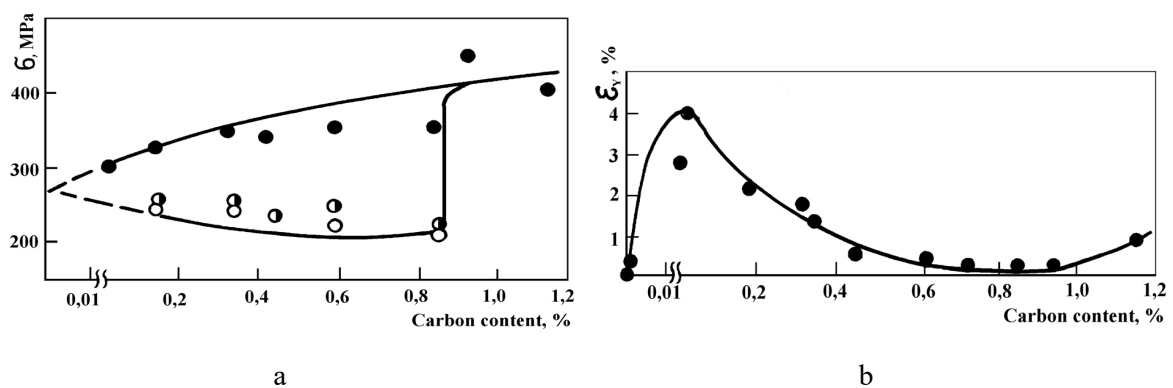


Figure 3. Effect of carbon content on plastic yield characteristics and onset of residual stress in Fe – C alloys: a) – macroscopic yield limit ●; yield limit of near surface layer ○; occurrence of residual stress ⦿; b) - change of the length of a yield plateau

Aiming to remove chemical heterogeneity, achieve equilibrium of a structure and remove the residual stresses arising at machining, the samples were subjected to homogenization in vacuum of $2 \cdot 10^{-4}$ mm Hg at 1040 °C temperature during 2 hours, cooled up to 840 °C, hold for 2 hours and then cooled together with the furnace. Mechanical properties of the steel are given in Table 2.

Table 2 - Mechanical properties of tested low-carbon steel specimens

Tensile strength R_m , MPa	Yield strength R_e , MPa	Elongation A , %	Contraction Z , %
650	330	14	40

Directly after heat treatment the near surface layer of about 60 μm depth was removed from each side of the sample by gradual electropolishing. Simultaneously the intermediate measurements of a deflection were carried out by optimizer. These actions, on the one hand, provided removal of near surface decarbonised layer, if such was after heat treatment, and on the other hand, gave an experimental confirmation of absence of residual stresses in the samples intended for further testing. Research of the microstructure of the samples showed the presence of equiaxial grains with an average diameter of 35 μm . After such preparation the samples were subjected to monotonic tension at strain rate $4,0 \cdot 10^{-4} \text{ s}^{-1}$ to various strain degrees (Figure 4). The working part of the tested specimens, designed for determination of the residual stresses, was cut out.

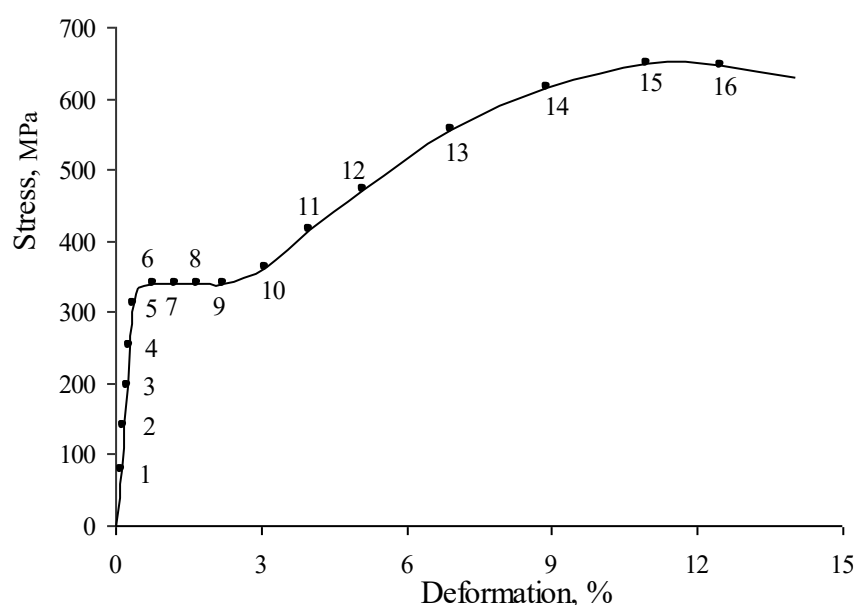


Figure 4. The monotonic tension diagram of carbon steel with various strain degrees (1 – 16) up to which samples were deformed

3. RESULTS AND DISCUSSION

Curves of the residual stresses, obtained for twelve samples, are shown in Figure 5. Various strain degrees, up to which samples were deformed and then measured residual stresses, were measured for a higher number of deformation degrees than it is shown in Figure 4. Analysis of these curves shows

that during the increase of sample deformation up to the upper macroscopical yield limit (samples 1 – 6), at a near-surface layer of a sample occur the compressive residual stresses, the magnitude of which gradually increases, and the maximum of the stresses moves to the surface of a sample. As soon as the sharp yield takes place (Lüders deformation), the magnitude of compressive residual stresses in the near-surface layer of the sample decreases (sample 7), and when the strain comes to the end of the yield plateau, the compressive residual stresses are changed to the tension stresses (samples 8 -10). At further strain increase (stage of strain hardening), in the near-surface layer of the sample the compressive residual stresses, which gradually increase occur again (samples 11 - 13). Having achieved the critical stresses value, when submicrocracks occur on the surface of metal, the compressive residual stresses decrease (sample 15), but they are not changed to the tension residual stresses.

In the stage of cracks propagation the residual stresses were not measured, since the neck had been formed on the deformable part of the sample. It should be mentioned that at the yield stage (samples 7 – 9), as well as at other stages, residual stresses were measured by mechanical method, using all deformable length of a sample. But at this stage (for example, in sample 8) in one part of the sample the Lüders front had already passed, and in the other - had not yet passed, therefore the values of residual stresses turned out to be conditional. The distribution of residual stresses in the near-surface layer of the sample just before the Lüders front starts to expand is illustrated by curve 6, and right after the passages of front by curve 10.

The first stage of process deformation (a stage of micro-yield) was investigated in great detail since it is less investigated, and meanwhile, namely this stage can explain many unclear phenomena [7]. Initial compression residual stresses (magnitude of 2 – 3 MPa) in near-surface layer of samples were found out at 60 MPa (the yield strength of an annealed material was 300 MPa). The depth of the deformed layer comprised approximately 100 μm . Moving away from the surface to the depth of the sample, in the beginning compression residual stresses increase, then they gradually decrease, and in the middle part of a sample they change into insignificant tension stresses.

With the increase of deformation, the magnitude of maximum compression residual stresses in a near-surface layer slowly grows (Figure 6, curve 1) up to the proportionality limit R_e (yield strength of a near-surface layer). Starting from R_e , a more intensive magnitude increase of these stresses (up to 40 MPa) was observed until the achievement of yield strength. The depth of the near-surface layer, in which primary plastic deformation proceeded, thus slightly decreased (from 100 up to 80 μm). At the stresses equal to 60 MPa the maximum magnitude of compression residual stresses was observed on depth of 35 μm (Figure 6, curve 2). With further increase of deformation it moved towards the surface of the sample. When it achieves the upper yield limit, the maximum stresses appears on the depth of 6 - 8 μm from the surface. It is necessary to note that in the stage of micro-yield (when R_e is achieved) micro-plastic deformation is observed in all volume of metal, but it does not render essential influence on the character of anomalous yield of a near-surface layer and distribution of residual stresses.

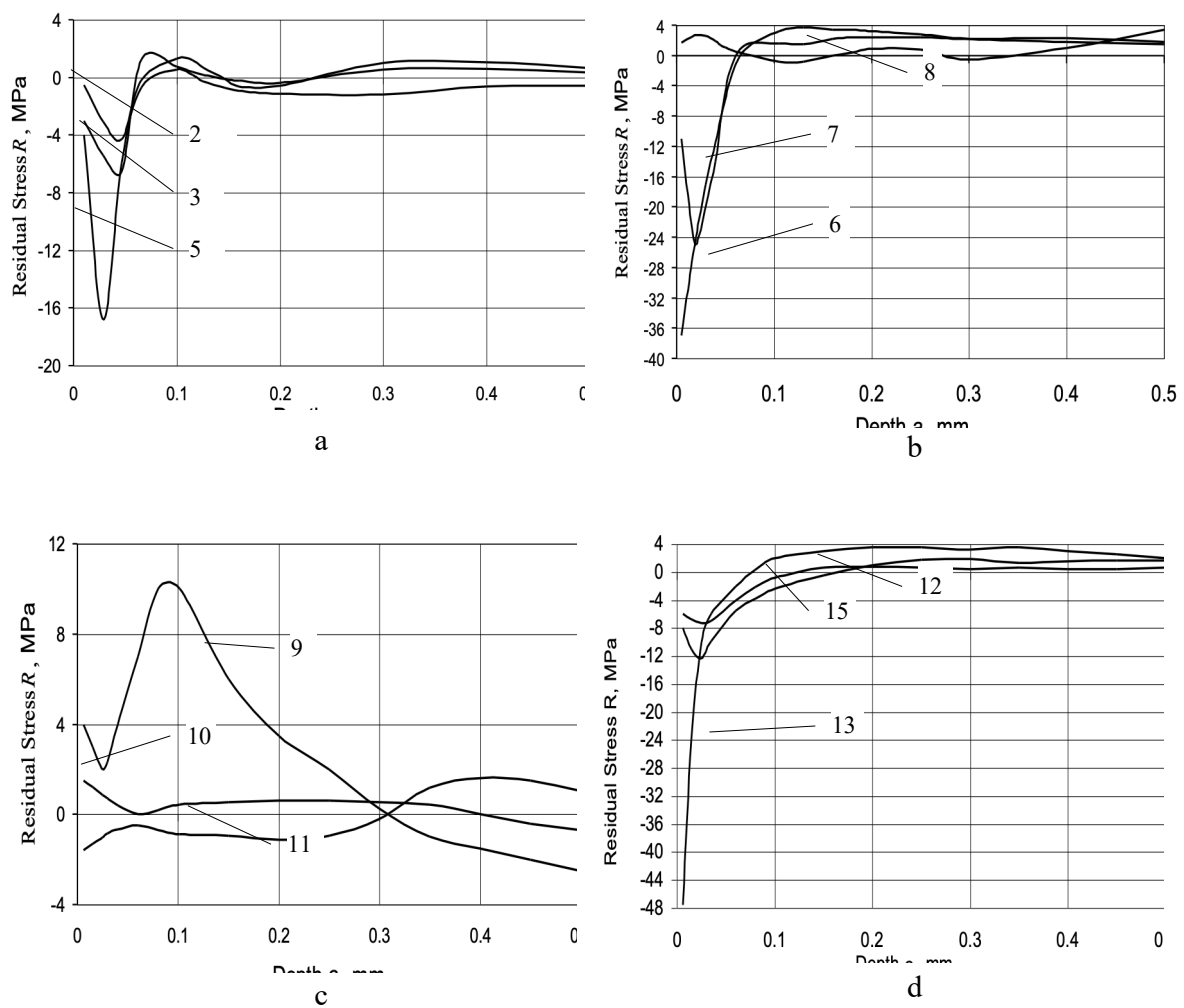


Figure 5. Distribution of residual stresses in a near-surface layer of a sample after various strain degrees. Curves are numbered according to deformation degree shown in Figure 4

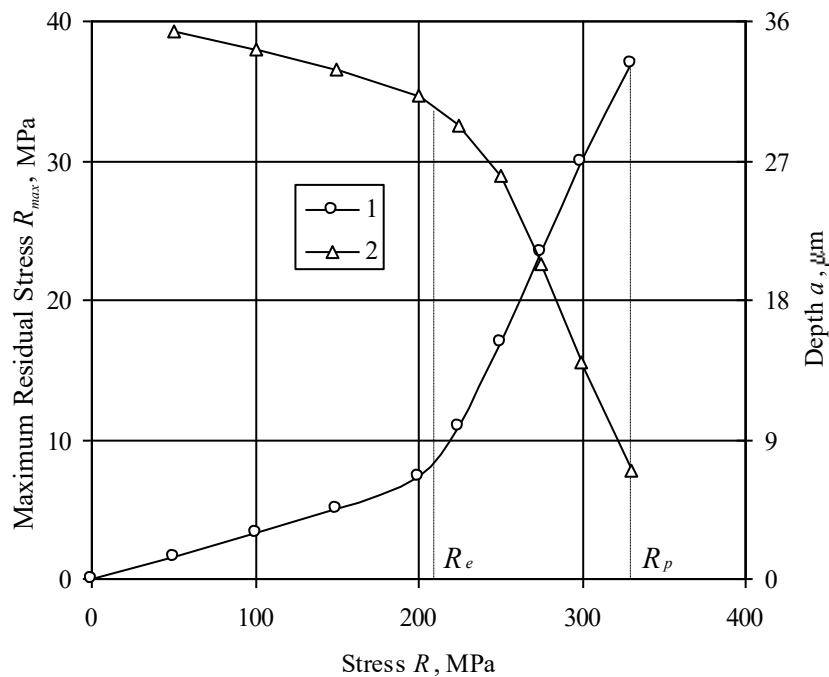


Figure 6. Distribution of the maximum residual stress R_{max} in near-surface layer of a sample depending on the applied stress R (curve 1) and the depth a (curve 2)

Hence, the maximum residual stresses are higher and they cover a thinner layer, when the plastic strain is bigger. This feature specifies that in the process of increase of plastic deformation in the stage of micro-yield, distinction between resistance to deformation of external and internal layers of metal continuously grows, and internal layers more and more influence a near-surface layer. It is interesting to compare the depth of hardened near-surface layer (80 - 100 μm) obtained in our experiments with the size of a grain of the investigated material. Microscopic investigation shows that the average diameter of a crystal grain of the investigated steel was 35 μm . Hence, optimum conditions of plastic deformation in near-surface layer are on depth equal to two-three crystal grain diameters. The obtained data show that the tension samples at various degrees of deformation up to the upper macroscopic yield limit results in residual stresses, which are compressing in thin near-surface layer, and tensile in the rest part of cross-section of a sample.

Formation of residual stresses testifies that at various degrees of monotonic tension a thin near-surface layer after unloading is aspired to preserve a bigger length than internal layers. In other words, a non-uniform plastic deformation has passed through the cross-section of the sample. It is related to a special condition of the near-surface layer of the polycrystalline material. Hence, this layer should have lower elastic strength limit. Due to its nature, a weakened near-surface layer because of plastic deformation is more strengthened than internal layers. Formation of such strengthened near-surface layer takes place directly in loading process in macro-elastic area of a sample. Until the moment when the stresses achieve the appropriate upper value of yield limit, the material in cross section subjected to deformation gets the following state: all not deformed volume of metal is surrounded by more rigid boundary of a near-surface layer (thickness 2 - 3 grains).

Thus, the data obtained in the present investigations on distribution of residual stresses in the stage of micro-yield give new proofs that the thin stronger near-surface layer can be formed until the upper yield limit is achieved. At the stresses, corresponding to the upper macroscopic yield limit, the ratio between the strength of near-surface layer and the strength of internal volumes of metal achieves the critical value, at which there is a fracture of this layer in the most narrow and weakest place of a sample. On the tension diagram the sharp drop of stresses (a tooth of yield) is observed. In the near-surface layer of the sample there is a decrease of the level of compressing residual stresses (Figure 5, samples 7 -9).

When the end of yield plateau is achieved, the compressing residual stresses in the near-surface layer of the sample turns into insignificant tensile residual stresses of approximately 10 MPa (Figure 5, sample 9). At the yield stage the levelling of residual stresses between the near-surface layer and a bulk of metal occurs. Thus a high degree of deformation of a near-surface layer may be preserved.

At the stage of deformation hardening a gradual increase of barrier effect of a near-surface layer and development of compressing residual stresses is observed in it (Figure 5, samples 11 - 13). Compression residual stresses arise in the near-surface layer of 80 - 150 μm thickness, and their maximum value achieves 50 MPa. At this stage, as well as at the stage of micro-yield, it is noticed that with the increase of deformation, the maximum of compression residual stresses is displaced to the surface of the sample.

Deformation of metal at the stage of deformation hardening causes a formation of critical dislocation density in local volumes near-surface layer, and therefore, in a near-surface layer of metal about 100 - 120 μm thickness submicroscopic cracks (found out by an inductive method [15 -17]) are formed. In a near-surface layer of a sample the level of compressing residual stresses begin to decrease (Figure 5, sample 15). Hence, at the stage of deformation hardening the decrease of compression residual stresses may be related to two reasons: a) reduction of a gradient of dislocation density between the basic volume of metal and near-surface layer; b) cracks formation in the near-surface layer of the sample.

Further strain increase results in the accumulation of submicroscopic cracks. By the end of the deformation hardening stage, microcracks are noticed both in internal volumes of a material, and in a near-surface layer of metal, where they achieve the critical size. In the period of cracks propagation, cracks grow till the macroscopic size, they are critically opened and the material finally collapses.

The obtained experimental data confirm hypothesis [2, 7], stating that the tooth and yield plateau on the tension curve are formed in the case when macro-yield of all material volume is preceded by plastic yield of the near-surface layer the depth of which is about the grain size.

During electrolytic removal of near surface layer, residual compression stresses decrease and on the certain depth their magnitude becomes equal to zero. The equilibrating tensile stresses disappear also. The disappearance of residual stresses after etching of near surface layer thickness about 100 μm convincingly proves, that at micro-yield stage plastic deformation is basically near surface process and on the nature has smaller resistance to deformation of near surface layer.

Thus, the analysis of the obtained experimental data confirms the anomalies of micro-plastic flow near to a free surface of a solid body and its rather essential influence on the general character and kinetics of macroscopic deformation of metals. It may be assumed also that, if in a material there will be no conditions for formation of near surface layer, which has increased dislocation density, then its deformation in an initial state would not result both the yield tooth and physical yield limit.

4. CONCLUSIONS

The sign, magnitude and character of distribution of residual stresses in cross-section of a sample in micro-yield, yield and strain hardening stages of monotonic deformation, were investigated. The tension samples at various degrees of deformation up to the upper macroscopic yield limit (stage of micro-yield) result in residual stresses, which are compressing in a thin near-surface layer and tensile in the rest part of cross-section of a sample. Because of plastic deformation the near-surface layer is strengthened more than the internal layers. Formation of such strengthened near-surface layer takes place directly in loading process in macro-elastic area of a sample. Heterogeneity of plastic deformation between the basic volume of metal and near-surface layer was also discovered in yield and strain hardening stages of monotonic deformation. Obtained experimental data shows the peculiarity of micro-plastic flow near a free surface of a solid body and its rather significant influence on the general character and kinetics of macroscopic deformation of metals.

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