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DISTRIBUTION OF RESIDUAL STRESSES IN NEAR-SURFACE LAYER OF CARBON STEEL AT MONOTONIC TENSION LOADING

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

Raspored zaostalih naprezanja u podpovršinskim slojevima ugljičnog čelika pri ispitivanju na vlak. Zadatak je istraživanja proučavanje karaktera rasporeda, veličine i oznake zaostalih naprezanja po presjeku uzorka pri statičkoj deformaciji (vlačno naprezanje) u stadiju mikro granice razvlačenja, granice razvlačenja i deformacijskog očvršćavanja. Analize dobivenih eksperimentalnih rezultata svjedoče o karakteru mikroplastičnog razvlačenja u podpovršini krutog tijela i njegovom bitnom utjecaju na opći karakter i kinetiku mikroskopske deformacije metala.

Ključne riječi: zaostala naprezanja, ugljični čelik, podpovršinski sloj, ispitivanje na vlak, mikronejednorodne deformacije

INTRODUCTION

At present, in literature there is a great amount of experimental data on the influence of various factors on mechanical characteristics of materials. 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 a near surface layer and in volume of a material proceeded differently. 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 [1 - 3].

At present, investigating fracture processes of metals with body-centred cubic (BCC) lattice it is accepted to divide all process of strain accumulation and fracture into four stages [4]. The first stage – *stage of micro-yield*, lasts from the beginning of the loading until the occurrence of the first lines of sliding (Lüders lines) on the yield plateau [5]. At this stage such characteristics as a limit of proportionality and a limit of elasticity are determined. The second stage - *stage of yield*, is characterized by non-homogeneous deformation in the form of front Lüders passing along all working length of a sample. The third stage – *stage of strain hardening*, at certain critical stresses submicrocracks with the size of approximately 1 - 3 μm occur on the surface layer of metal. This stage finishes at the moment, when maximal load is achieved and the neck formation begins. The fourth stage – *stage of cracks propagation*, starts from the beginning of neck formation until the final fracture of a specimen.

The contradictory data on residual stresses arising in a near-surface layer of a specimen during deformation have still been published in literature [6 - 8]. 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.

EXPERIMENTAL CONDITIONS

A device, 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 used to define residual stresses [9]. The near-surface layer was removed by electrolytic etching. 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

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from the top side of a sample, were calculated, according to the relationship [9]:

$$\sigma(a)=\frac{4E}{3l^2}\,[(h-a)^2\frac{df}{da}(a)-4(h-a)f(a)+2\,]\int_0^{\alpha}\phi(\xi)\delta\xi] \quad (1)$$

with:

E - modulus of elasticity of a material;

l - the length of a sample;

h - sample thickness;

f - deflection in the middle of a sample and

ξ - distance from the surface of a sample.

Chemical composition of the tested carbon steel samples was (%): C – 0,45, Si – 0,24, Mn – 0,60, Cr – 0,20, P – 0,03, S – 0,03, Ni – 0,20. Plain samples with the dimensions of a working part 2×16×60 mm were produced from sheets of this steel. 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 $2\cdot10^{-4}$ 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 tested after heat treatments were: R_p – 330 MPa, R_m – 650 MPa, A – 14 %, Z – 40 %.

After such preparation the samples were subjected to monotonic tension at strain rate $4{,}0\cdot10^{-4}$ s^{-1} to various strain degrees (Figure 1.).

RESULTS AND DISCUSSION

Curves of the residual stresses, obtained for nine samples, are shown in Figure 2. 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 1. Analysis of these curves shows that during the increase of sample deformation up to the upper macroscopical yield limit (samples 1 – 3), 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 4), and when the strain comes to the end of the yield plateau, the compressive residual stresses are changed to the tension stresses (samples 5, 6). 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 7, 8). Having achieved the critical stresses value, when submicrocracks occur on the surface of metal, the compressive residual stresses decrease (sample 9), but they are not changed to the tension residual stresses.

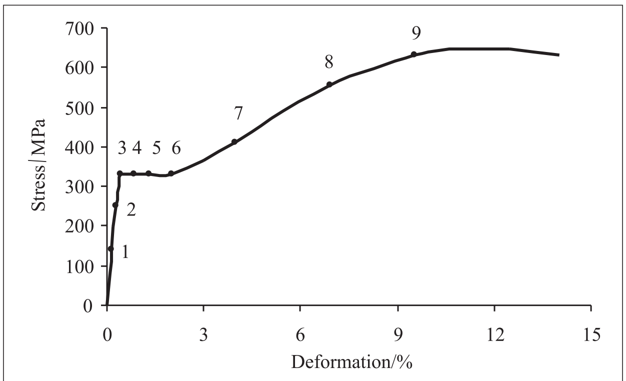

Figure 1. The monotonic tension diagram of carbon steel with various strain degrees (1 – 9) up to which samples were deformed

It should be mentioned that at the yield stage (samples 4 – 6), 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 5) 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 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 [4]. 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 (samples 1 – 3).

With the increase of deformation, the magnitude of maximum compression residual stresses in a near-surface layer slowly grows (Figure 3, 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. At the stresses equal to 60 MPa the maximum magnitude of compression residual stresses was observed on depth of 35 μm (Figure 3, 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.

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 mate-

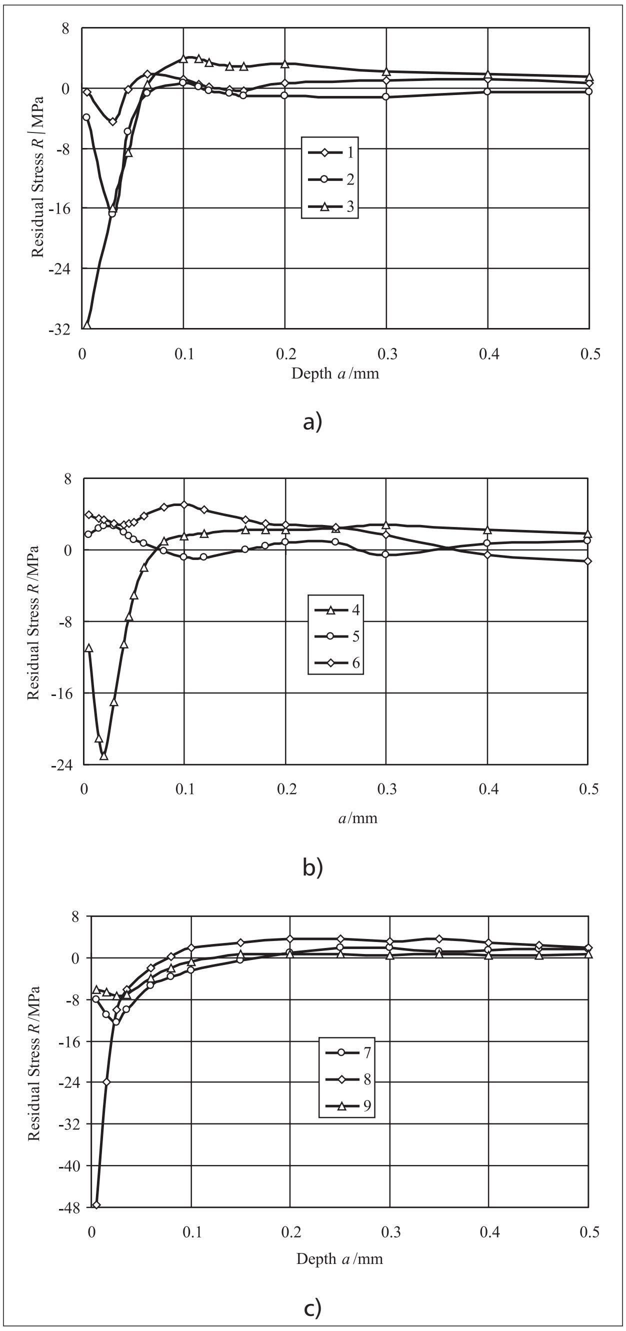

Figure 2. Distribution of residual stresses in a near-surface layer of a sample after various strain degrees. Curves are numbered according to deformation degree shown in Figure 1: a – residual stresses in micro-yield, b - residual stresses in yield stage, c - residual stresses in strain hardening stage

rial. 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

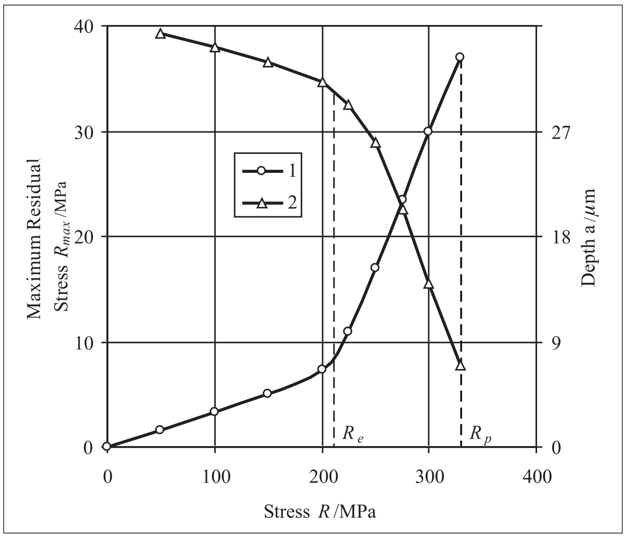

Figure 3. Distribution of the maximum residual stresses R_{max} in near-surface layer of a sample depending on the applied stresses R (curve 1) and the depth a (curve 2)

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).

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 2, samples 4, 5). 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 5 MPa (Figure 2, sample 6). At the yield stage the levelling of residual stresses between the near-surface layer and a bulk of metal occurs.

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 2, samples 7, 8). 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 [10]) are formed. In a near-surface layer of a sample the level of compressing residual stresses begin to decrease (Figure 2, sample 9). 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.

The obtained experimental data confirm hypothesis [1, 4], 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.

CONCLUSIONS

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, 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. 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.

REFERENCES

[1] J.R. Kramer, R. Pangborn, S. Weissmann, Proceedings, 27th Sagamore Army Mater. Res. Conf., Lake George, N.Y., 1980, New York – London, 1983, pp. 103-117.

[2] C.H. Wu, J. Hsu, C.H. Chen, Acta mater. 46 (1998), 3755-3760.

[3] A.G. Kolmakov, G.V. Vstovsky, Materials Science and Technology, 15 (1999), 705-710.

[4] V.F. Terentjev, Ustalost metalliceskih materialov, Moskva, Nauka, 2002, pp. 37-42 and 172-186.

[5] H.B. Suna, F. Yoshidaa, M. Ohmorib, X. Ma, Materials Letters, 57 (2003) 4535-4539.

[6] E. Capello, Journal of Materials Processing Technology, 160 (2005), 221-228.

[7] G. Schleinzer, F.D. Fischer, International Journal of Mechanical Sciences, 43 (2001), 2281-2295.

[8] J. Johansson, M. Odean, X.-H. Zeng, Acta mater., 47 (1999) 9, 2669-2684.

[9] J. Vilys, V. Ciuplys, V. Terentjev, A. Kolmakov, V. Kvedaras, Particularies of plastic deformation of metals near surface layers, Kaunas, Technologija, 2003, pp. 11-26 and 56-60.

[10] V. Augutis, R. Ramanauskas, A. Ciuplys, J. Vilys, V. Ciuplys, Materials science (Medziagotyra), 1 (2006), 84-87.

Note: Responsible translator is the author Stasys Bockus.