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EFFECT OF DEFORMED SURFACE LAYER ON METAL ELASTIC PROPERTIES

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KAUNO TECHNOLOGIJOS UNIVERSITETAS
KTU FIZIKINĖS ELEKTRONIKOS INSTITUTAS

Antanas Čiuplys

DEFORMUOTO PAVIRŠINIO SLUOKSNIO ĮTAKA ELASTINĖMS METALŲ SAVYBĖMS

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Relevance of the Work

One of the most important objectives of today science and technology is to develop high quality machines and structures, to decrease costs of their production, as well as consumption of metals and energy, to implement efficient technological processes and materials at the same time increasing their lifetime. One of the ways to achieve this goal is improvement of mechanical, physical and chemical properties of machine parts working surface. It predetermines lifetime and reliability of the parts and a machine is general. Strengthening of surface parts enables to substitute expensive metals by cheaper ones, and, by improving their surface quality, not decrease but sometimes even to increase reliability of entire, structure.

Strengthening of surface layer of a structural material by use of certain technological influence method enables to solve a lot of technical problems of high importance, despite that development and implementation of the strengthening methods itself is complicated scientific and production problem. In spite of this, the progress of surface strengthening technologies is obvious. It ensures continues improvement of machine parts and tool operational characteristics – their life and wear resistance as well as increase of reliability of most important structural elements and increase of resistance of structural materials to various damaging factors: high alternating loads, aggressive environment and high temperature gradients.

Strength problem is very acute in nowadays technical world. There is a great amount of methods enabling to increase of strength of both materials and tools on structures made of them. But in spite of ability of these methods demand always exceeds the supply. That is why in the solution of machine building, metallurgy and other industry branches development problems, the realization of material strength reserve by application of known, strengthening methods and development of new ones is of paramount importance.

In some cases machine building need materials of very high plasticity, in other cares materials is strengthened by reduction of plasticity. Mechanical properties of material can be improved by two different ways. One way is to remove material defects, so called dislocation, which are violation of regular atoms order in metal. Such dislocation can reduce metal strength up to thousand times. Recently metal crystals without defects had been produced, but they are very small and their practical application is rare. Simpler is second way which means increase dislocation number in the metal. Around the dislocation additives are concentrated, there additives are blocking deformation planes, what means that the metal becomes stronger and higher force is needed to deform it. This feature allows improve mechanical properties of a metal.

During machine part operation metal surface is subjected to highest loads, there most often the fracture starts, and it propagates into inner layer of the part. Production of machine part, critical structural elements and tolling is aimed at achievement of very strong, hard and wear resistant surface and more mild and plastic care. Choice of suitable part and structural elements surface strengthening means allows use lower quality metal without negative effects on reliability. Such solution of the problem is simpler, more convenient and less expensive.

Very often machine parts operate at high mechanical and thermal loads in corrosive or abrasive environment. Therefore, both new structural materials are needed, like foe example, high-alloyed steels and alloys, and advanced surface strengthening technologies enabling to form coating of necessary properties. Change of chemical composition alone, e.g. alloying, allows to improve service characteristics of steels and their alloys but is does not solve nowadays machine building problems. This way requires great amount of expensive and rare metals such as Chromium, Nickel, Molybdenum, Vanadium, Tungsten and others.

Therefore, the less costly way is to change chemical composition and properties not of entire material volume, but the surface layer only, because protection of parts and structures against mechanical wear or corrosion depends on the properties of surface layer only.

It is well known that characteristics of plasticity and fracture vary depending on conditions of surface layer, behavior and environment. That is why investigation of surface layer plastic strain peculiarities during deformation of metallic materials (monotonic deformation, fatigue, creep, wear, etc.) It’s important from theoretical and practical point of view. Thus, any metallic materials strengthening or fracture theory should take into account surface effects.

Improvement of machines and structures reliability and lifetime can be achieved by details and thorough investigation of plastic strain peculiarities in micro and macro volumes of solid body. It is necessary when plastic strain formation kinetics and various non homogeneity forms are analyzed. Such investigations are important for the development of new means for improvement of metallic materials properties, including resistance to fracture at various loads.

The Objective and Tasks of the Work

The objective of the investigation is to analyze effect of surface layer on mechanical properties of metal. The following tasks had been anticipated to achieve the objective:

- Investigate peculiarities of plastic strain at monotonic and cyclic loading of metals;
- Investigate effect of hardened surface layer on mechanical properties of metal;

- Investigate effect of metal surface layer on deformation ageing process;
- Investigate yield plateau formation conditions at monotonic loading of metal with body-centered cubic (BCC) lattice;
- Investigate role of surface layer at Haasen-Kelly effect;
- By use of multifractal parameterization investigate evolution of surface layer dislocation structures at monotonic and cyclic deformation.

Methods of the Investigation

Mechanical characteristics of metals were defined by monotonic tension and high cycle fatigue tests. Special device for round cross-section specimens' surface layer hardening was produced and it was used for evaluation of the hardened surface layer effect on a steel mechanical characteristics. Plate type specimens were hardened by rollers. Depth of the hardened specimen surface layer was measured using for the first time for this purpose Barkhauzen's method. For the investigation of dislocation structures foil production on the specimen surface or at any desirable depth procedure was developed. For the quantitative evaluation of dislocation structures new multifractal parameterization method was used. Calculation of multifractal characteristics was performed by use of *MFRDrom* software.

Scientific Novelty and Practical Significance

Using magnetic Barkhauzen's method new hardened layer depth measuring method enabling non-destructive depth measuring was developed. Reasons of yield plateau formation at monotonic loading of BCC metals are investigated. Peculiarities of plastic deformation at monotonic and cyclic loading, influence of surface layer on Haasen-Kelly effect, influence of hardened surface layer on the metal mechanical characteristics and effect of metal surface layer on deformation ageing process are investigated.

Method of dislocation structure investigation on the specimen surface or at any desirable depth is developed.

New multifractal parameterization method for quantitative dislocation structures evaluation, enabling to account for dislocation structures characteristics and their evolution at monotonic and cyclic loading, was used.

The result obtained can be used for choosing metal manufacturing regimes, improving mechanical technological and operational properties of machine parts and structures at the same time decreasing their cost and increasing lifetime.

Approbation and Publication of the Work

Results of the investigation are published in five reviewed publications and in twelve articles in the various conference proceedings. Results of the dissertation were presented and discussed in ten international and three national scientific conferences.

The Author Defends

- Hardened layer depth measurement method based on magnetic Barkhauzen's method, what enables to define the layer depth without destruction of the specimen;
- Results of investigation of deformation process peculiarities and dislocation structure evolution in the metal surface layer at monotonic and cyclic loading;
- Results of investigation of metal surface layer influence on Haasen-Kelly effect;
- Investigation results of the effect of metal surface hardening on the form of monotonic tension curve and on metal mechanical properties;
- Investigation results on the effect of cyclic loading on the length of yield plateau at monotonic deformation;
- Investigation results on effect of metal surface layer on deformation ageing process;
- Use of multifractal parameterization method for description of a metal surface layer dislocation structures formation peculiarities at monotonic and cyclic loading.

Structure and Size of the Work

Dissertation consists of introduction, three main chapters, general conclusions and recommendations, list of references, and list of author's publications on the subject of dissertation. List of references includes 180 bibliographic sources. Volume of the work is 133 pages, including 69 figures and 7 tables.

In the first chapter *review of literature sources* on the subject of dissertation is presented. Analysis of literature sources reveled that at the moment there is no unanimous opinion about surface layers behavior at plastic deformation. But great majority of the authors consider the surface layer like having significant effect on general plastic deformation process.

Aiming to analyze comprehensively processes, taking place in the metal surface layer at various loading conditions, in the end of the chapter the objective of investigation and main tasks are formulated.

In the second chapter *the experimental method*, equipment and devices are described. Mechanical properties of metals were determined by monotonic tension and cyclic tension-compression tests. Aiming to obtain more precise results standard testing machines with refined test data acquisition devices were used in the investigation. Special round cross-section specimen surface layer hardening device for investigation of the surface layer effect on steel mechanical properties was developed and produced. Plate form specimens were hardened by rollers. Depth of specimen hardened layer was measured using for the first time for this purpose magnetic Barkhauzen’s method.

New foil, assigned for investigation of dislocation structures, production method is developed, that enabled to produce the foils on the specimen surface, or at any desirable depth.

Mew multifractal parametrization method was used for quantitative dislocation structures evaluation; this method enabled to account for dislocation structures characteristics and their evolution at monotonic and cyclic loading. Computer software *MFRDrom* was used for computation of multifractal characteristics.

In the third chapter (*experimental*) test results are presented.

Effect of both compression prestressed and hardened surface layer depth on mechanical properties of middle-carbon steel with BCC lattice was investigated. Chemical composition of the steel is presented in the Table 1. Two series of specimens were made from steel:

1) Round cross-section specimens with 100 mm working part length and 10 mm diameter;
2) Plate type specimens with 60 mm working part length 10 mm width and 3 mm thickness.

Table 1

Chemical composition of steel

Chemical composition, %. The rest – Fe							
C	Mn	Si	Cr	Ni	S	P	Cu
0.35	0.95	0.75	0.30	0.30	0.045	0.040	0.30

After manufacturing both series of specimen were subjected to annealing for 1 h 30 min at 850 °C temperature. The annealing resulted formation of uniaxial grains with average diameter equal to 35 μm. Round cross-section specimens’ surface was strain hardened using specially made device for such specimens, and plate specimens were strain hardened by rollers.

Specimens were subjected to monotonic tension at room temperature by universal testing machine *УМЭ-10ТМ*. Strain rate for round cross-section specimens was 1.67×10^{-4} s^{-1}, and that for plane specimen – $2.78\times10^{-4}s^{-1}$. Tension diagrams were plotted by electronic X–Y recorder, which deformation scale was 10:1 or 65:1, and load scale – 250 N in 1 mm.

For all round cross-section specimens and for part of plain specimens the tension diagrams were constructed just after hardening at various degrees. The rest part of plate type specimens were subjected to tension after 3 h ageing at 100 ºC temperature. Depth of hardened layer for there specimens was defined by use of Barkhauzen's method. After surface hardening of the cylindrical specimens, the degree of cold working was defined. Initial mechanical characteristics of the steel were determined by monotonic tension tests of annealed not hardened specimens. The tension diagrams obtained were compared with those obtained by testing of hardened at various degrees specimen.

Obvious yield plateau was obtained for the round cross-section specimens, which surface layer was not subjected to cold working after annealing. Length of the yield plateau was $\varepsilon \approx 2.0$ %. it was revealed that small increase pf the degree of cold hardening results reduction of both the yield plateau length and yield strength, but the ultimate tensile strength stays almost unchanged.

When the cold working degree reaches 0.95 %, the yield plateau disappears, yield strength becomes minimal, and ultimate tensile strength starts to grow. At further increase of the cold working degree, the yield plateau does not appear and both proportional limit and ultimate tensile strength grow. Relative elongation A decreases a little at the increase of cold working degree. Rather large A volume ($A \cong 20$ %) remains even when the yield plateau disappears completely. At high cold working degrees relative elongation decreases to 16 %.

Analogous process took place at monotonic tension of plates. It's interesting to compare tension curves on Fig. 1, a (not hardened specimen) and b (specimen surface hardened at 110 µm depth). Until the proportionality limit curve b consider with curve a, later goes up (see dashed line) and at the end of curve a yield plateau again consider with it. Surface hardening at the 110 µm depth results disappearance of the yield plateau, increase of the ultimate tensile strength and the yield strength obtain minimal value.

Investigation of hardening depth effects on the mechanical characteristics of plate type steel specimens showed that increase of the hardening depth results more intense increase of the ultimate tensile strength of the specimens subjected to ageing. The ultimate tensile strength of not aged specimen at the beginning does not change, but it starts to increase, when the yield plateau disappears. When the specimen surface is hardened until 110 µm, the yield strength is minimal for the specimens subjected to monotonic tension just after hardening, and the yield strength is a little decreased for aged specimens, but it increase constantly with increase of the hardening depth. When the yield plateau disappears for not aged specimens (h = 110 μm), the aged specimens retain the yield plateau about ~ 1.5 %. It is retained even in the care, when hardening depth is increased three times. It was defined that for aged specimens yield plateau disappears on the condition that the hardening depth must be not less than 800 μm. analysis of the hardening depth effect on the relative elongation showed that at the increase of hardening depth the relative elongation of hardened and aged specimens decreases less than that specimens subjected to tension just after hardening.

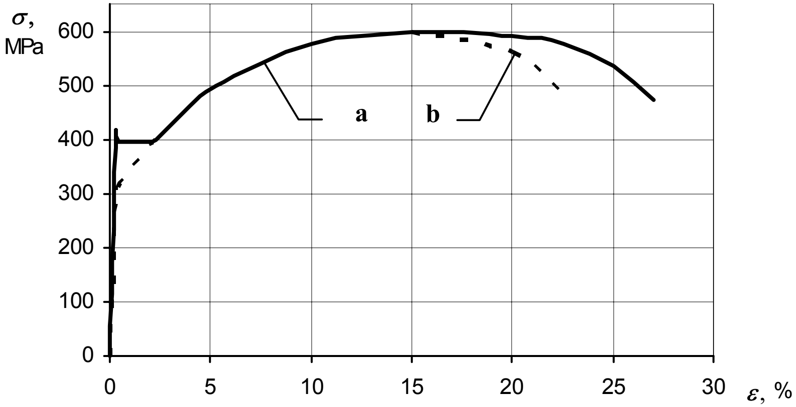


Fig. 1. Monotonic tension curve form changes for plate type specimens depending on cold working degree: a – not hardened specimen, b – specimen surface hardened at 110 μm depth

It was investigated how various degrees of cold working influence on duralumin, i.e. metal having face-centered cubic (FCC) lattice, monotonic tension curve form and mechanical characteristics. Chemical composition of the metal is presented in the Table 2.

Standard round cross-section specimens with the length of working part equal to 56 mm and diameter – 8 mm were made from duralumin. After mashing specimens were subjected to annealing for 2 hours at 400 °C temperature. The specimens were cooled with the furnace to 260°C and later – in the air atmosphere. Surface of the cylindrical specimens was hardened by special device. Specimens were subjected to monotonic tension at room temperature by universal testing machine *УМЭ-10ТМ.* Strain rate was 2.98×10^{-3} s^{-1}. The specimens were divided into two groups. Part of the first group specimens after annealing and work hardening were immediately subjected to monotonic tension. The rest specimens were this group after work hardening was subjected to ageing at various regimes: natural for 7 days, 15 hours and 25 hours in the boiling water. Specimens of the second group after annealing were subjected to hardening: heating to 500 ºC, hold for 50 min and water quenching. After the hardening the specimens were subjected to cold working and ageing at the same regimes, as those not hardened.

Table 2

Chemical composition of duralumin

Chemical composition, %. The rest – Al						
Cu	Mg	Mn	Fe	Si	Zn	Ti
4.2	0.6	0.7	0.5	0.6	0.25	0.1

An experimental data show that increase of strain hardening degree results reduction of duralumin relative elongation. This reduction is larger for hardened specimens than that for annealed ones. Ultimate tensile strength increase negligibly for both annealed and hardened specimens, but increase of the proportionality limit is obvious. After strain hardening both annealed and hardened specimens were subjected to ageing at various regimes. This procedure had not strong effect on the mechanical characteristics of the annealed specimens.

Figure 2 shows the changes of monotonic tension curve of duralumin specimen subjected to various degrees of strain hardening. It is obvious that the yield plateau is not formed neither at monotonic tension of the annealed specimens, nor at their hardening at various degrees.

If on annealed duralumin specimen is subjected to some tension, i.e. to some degree of deformation, followed by remove of the load and repeated tension, then in the tension curve small yield plateau develops. It means that plastic deformation process is influenced by the direction of initial plastic deformation: it is important, if the direction of initial plastic deformation coincides with the direction of later deformation or not.

It is interesting to note that for metals, having FCC lattice, increase of strain hardening degree at small hardening values does not result decrease of the proportionality limit, as it happens for metals, having BCC lattice.

Phenomena described are related to hardening of surface layer and it's interaction with not deformed central part of the specimen, as well as with residual stresses formed in the surface layer, with strain ageing and Baushinger and Haasen-Kelly effects.

Based on the results obtained, it may be stated that plastic deformation processes in BCC and FCC lattice metals are going on in different way. Surface hardening has strong effect on the metal mechanical characteristics, especially on BCC lattice metals.

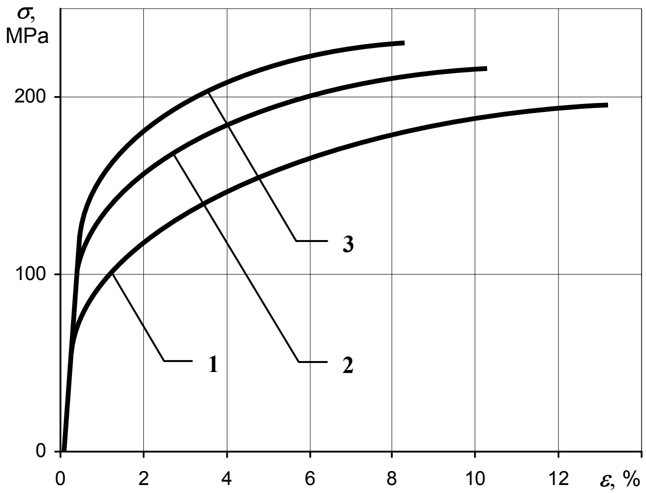


Fig. 2. Changes of the monotonic tension curve form for annealed duralumin specimen subjected to various degrees of strain hardening: 1 – annealed specimen, 2 – strain hardening 0.7 %, 3 – strain hardening 1.8 %

Strong effect on general plastic deformation process also has the circumstance, if the direction of initial plastic strain coincides with that of later plastic strain.

Influence of strengthening layer depth on fatigue strength of middle-carbon steel was investigated as well. Tests were carried out on specimens with diameter of working part equal to 10 mm. Before hardening the specimens were subjected to 2 h annealing at 850 ºC temperature. Surface of the specimens working part was hardened in the round cross-section specimens hardening device.

Tension-compression fatigue tests were carried out with four series of the specimens. Depth of the hardening layer and fatigue limit presented in the Table 3.

Table 3

Thickness of the hardening layer and fatigue limit for middle-carbon steel

Series number	Thickness of the hardening layer, mm	Fatigue limit σ_R, MPa
1	0	344
2	0.1 – 0.2	364
3	0.3 – 0.4	372
4	0.5 – 0.6	374

Dependence of the fatigue limit on thickness of hardened layer presented in Fig. 3. The data show that surface hardening increases fatigue limit and lifetime.

Most of all fatigue limit is increased by strain hardening at 0.1 – 0.2 mm depth. Fatigue limit in such case increase at 20 MPa, and lifetime at 400 MPa stress increases from 1.5×10^4 to 10^5 in comparison with not hardened specimen. Further increase of the hardened layer depth results reduction of the increase of fatigue strength and lifetime. Hardening at 0.5 – 0.6 mm layer depth in comparison with 0.3 – 0.4 mm depth results the same fatigue limit value.

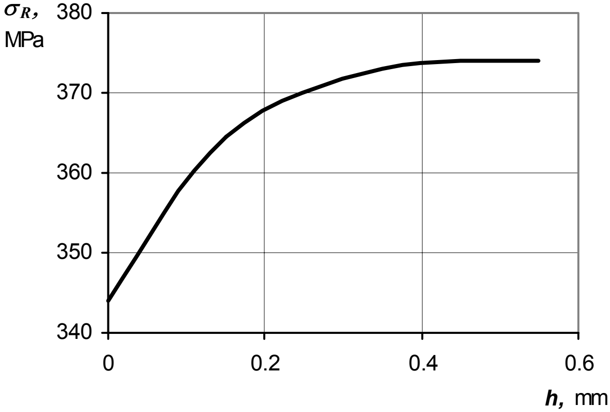


Fig. 3 Effect of the depth of hardened layer on the steel cyclic strength

The curve, showing dependence of the steel fatigue limit from the depth of hardened layer (Fig. 3), allows to conclude that maximum fatigue strength increase is achieved at hardened layer depth equal to 0.3 – 0.4 mm. Increase of the hardened layer depth over 0.5 mm has no strong effect on the cyclic strength.

Effect of loaded specimen ageing on monotonic tension curve form and mechanical characteristics of middle-carbon steel was investigated as well. Round cross-section specimens of the same form as there, used for investigation of the effect of stain hardening on mechanical characteristics by monotonic tension tests, were used.

Initial mechanical characteristics of the steel were determined in monotonic tension tests of annealed specimens. Tension curve obtained was compared with curves obtained in the tests with specimen ageing under stress. When the load increase was ceased and during ageing under stress, the stress at the beginning a little decreased due to relaxation process. When the ageing was finished, the specimens were subjected to monotonic tension to the fracture.

After the fracture relative elongation and reduction of cross-section area were measured.

In the tests the ageing under stress time and prestrain before ageing value were varied. Tests showed that reduction of cross-section area approximately equal for the aged and not aged specimens. Thus, this characteristic is not sensitive to ageing; therefore, change of the steel plastic properties after ageing should be evaluated by use of relative elongation *A*.

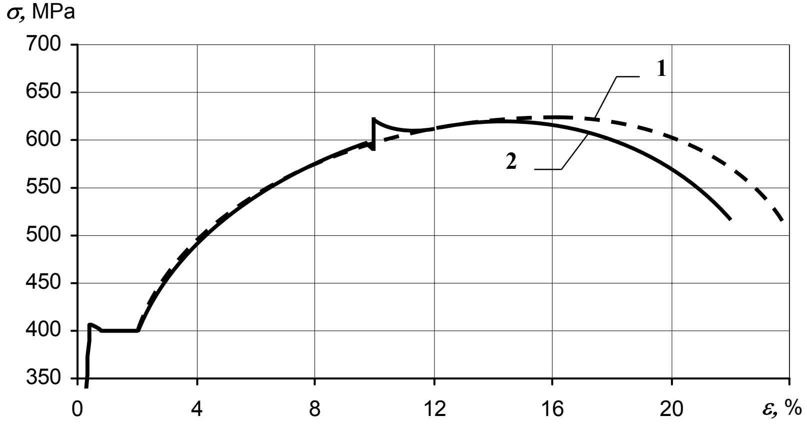


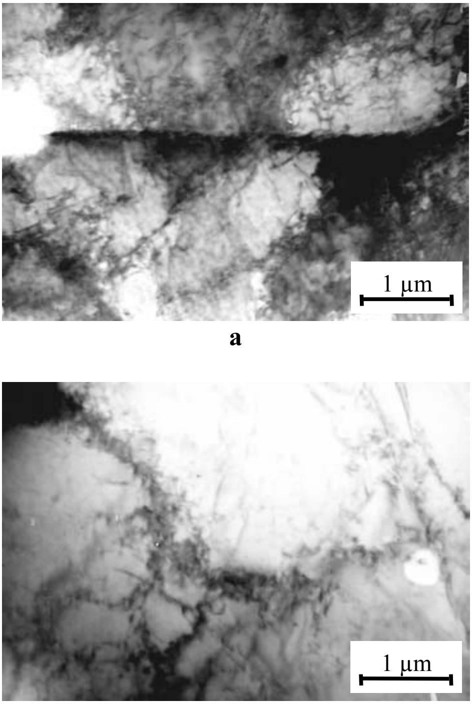
Fig. 4. Monotonic tension curves for the steel: 1 – continuous deformation; 2 – after 15 hours ageing under stress and 10 % prestrain

Figure 4 shows that 15 h ageing of prestrained at 10 % specimens results characteristics ”peak” in the monotonic tension curve, which can achieved and even exceed ultimate tensile strength of the steel. Reduction of steel plastic characteristics in this case is rather small. Relative elongation *A* of the not aged specimen equals to 24 %, and that of 15 hours aged specimen – 22 %.

At the same initial strain ($\varepsilon \approx 10$ %) increase of ageing time results change of the monotonic tension curve form. The newly formed peak growths and steel plasticity decreases. After 60 h ageing relative elongation decreases to 19 %, and after 180 h ageing – 17 %.

It was revealed that decrease of steel plastic characteristics depends on the strain value before ageing. At 5 % prestrain and following ageing during 60 h and 180 h, the small characteristic peak is formed in the monotonic tension curve, and the curve differs very little from those of not aged specimens. Increase of the prestrain and following ageing under stress result increase of the peak. Longer ageing time results reduction of the steel plasticity.

Dislocations predetermine above described metal mechanical characteristics changes. Density of dislocation sources near the surface is higher than inside the metal. Therefore, during plastic deformation more dislocations are formed in the surface layer than in inner metal layers. Dislocation formation is facilitated by large surface free energy, small defect energy, free surface and others. Dislocation structure of a steel specimen, subjected to 5 % strain, on the surface and in 3 mm depth, is shown in the Figure 5.



a

b

Fig. 5. Dislocation structure of the steel subjected to 5 % strain: a – on the specimen surface, b – in 3 mm depth

In order to clear up effect of surface layer on a metal plastic strain, influence of this layer on Haasen-Kelly effect was investigated. It means that at repeated loading of the steel specimens, the yield point on monotonic tension curve formation reasons were investigated.

Plate specimens of the same form as those, used in monotonic tension tests for investigation of hardened layer depth effect on mechanical characteristics, were applied.

Some specimens after unloading were subjected to electrolyte etching in order to remove surface layer. Chemical composition of the electrolyte: 850 ml orthophosphorus acid (H_3PO_4), 150 ml sulphur acid (H_2SO_4), and 50 g Chromium oxide (CrO_3).

Monotonic tension curve changes during repeated deformation were investigated. For the purpose, the specimens were loaded over the yield strength, then unloaded and reloaded. Monotonic tension curves show that unloading and repeated loading results yield point. This effect takes place and after 2, 3 and 4 unloading – reloading cycles. Also it was noticed that the yield point had been formed and after partial unloading, when the load had been reduced at about 100 MPa.

The following special test was carried out aiming to evaluate effect of surface layer on metal plastic deformation. After 4 % prestrain, when the yield plateau is passed, the load was taken off and by electrolyte etching 0.04 mm depth surface layer was removed; after this procedure the specimen was loaded again. Repeated loading of the specimen results disappearance of the yield point (Fig. 6, point A).

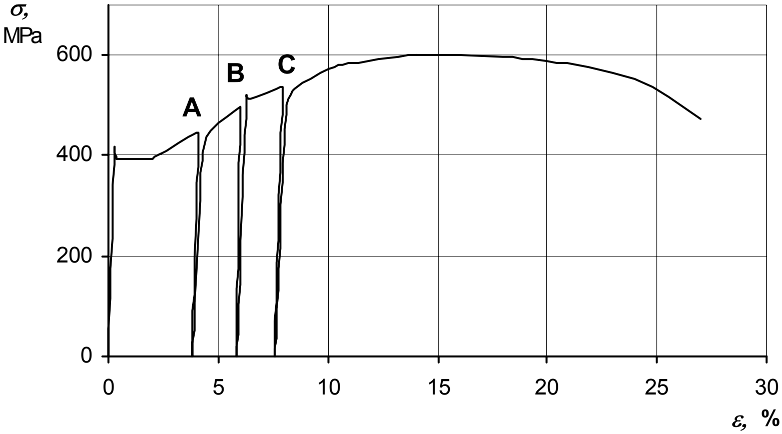


Fig. 6. Change of the tension diagram with repetitive unloading-reloading cycles, when surface layer of 0.04 mm was removed at points A and C after unloading

If at the further deformation the stress in the point B (Fig. 6) is taken off again and specimen loaded immediately without removal of the surface layer, then yield point arises again, as it may be seen from the curve. In the third cycle (Fig. 6, point C) after unloading the surface layer was removed again. Following loading of the specimen, results disappearance of the yield point again. There tests show especial surface layer effect on the metal plastic deformation.

Based on the theoretical and experimental literature sources and taking into account our investigation data it may be concluded that unless there is no possibility to form in the metal a surface layer with higher dislocation density, then during deformation neither yield point nor yield plateau will be formed. In order to form clear yield point or yield plateau, the corresponding relation among surface layers and inner layers strength should exist.

Aiming to clear up deformation peculiarities at monotonic and cyclic loading of a metal, kinetics of yield plateau changes during cyclic loading was investigated. Plate type low-carbon steel specimens were used for the tests. Chemical composition of steel is presented in Table 4.

Table 4

Chemical composition of steel

Chemical composition, %. The rest – Fe						
C	Si	Mn	Cr	P	S	As
0.18	0.2	0.45	0.15	0.035	0.040	0.08

In order to remove internal stress and to obtain uniform structure in entire specimen cross-section, the specimens were annealed for 1 h 30 min at 875 ºC temperature in vacuum (10^{-4} mm Hg column). After annealing uniaxial grains average diameter of ~ 30 μm were formed. Mechanical properties obtained are presented in Table 5.

Table 5

Mechanical properties of steel

Tensile strength R_m, MPa	Yield strength R_e, MPa	Elongation A, %	Contraction Z, %	Fatigue limit σ_{R}, MPa
395	240	25	37	220

The specimens were deformed at room temperature by universal tension machine *Instron TT-DM*. Repeated tension fatigue tests were carried out by fatigue *Shenk* type pulsator at 2800 cycles/min loading frequency at constant $\sigma = 230$ MPa load.

In course of yield plateau changes kinetics investigation at cyclic loading, part of the specimens after certain number of loading cycles were taken out of the pulsator and immediately subjected to monotonic tension. Monotonic tension tests carried out at 2.78×10^{-3} s^{-1} strain rate. Elongation along the deformation axis was registered at scale 200:1. This circumstance allowed to determine with necessary precision length of yield plateau and other tension diagram parameters. Mechanical properties of the steel were determined by testing of annealed specimens. The yield plateau and yield point are clearly seen on the tension curve. Length of the yield plateau of annealed specimens was 2.6 % – 2.8 %.

Figure 7 shows experimental data obtained in course of yield plateau form and length change kinetics investigation after fatigue loading, when maximum repeated tension load had been 230 MPa. The data show that cyclic load after some incubation, which for assumed load 230 MPa equals to ~ 10^2 cycles, abolishes the yield point, and later, at continuous growth of the number of loading cycles, causes continuous yield plateau length decrease till complete disappearance in the monotonic tension curve.

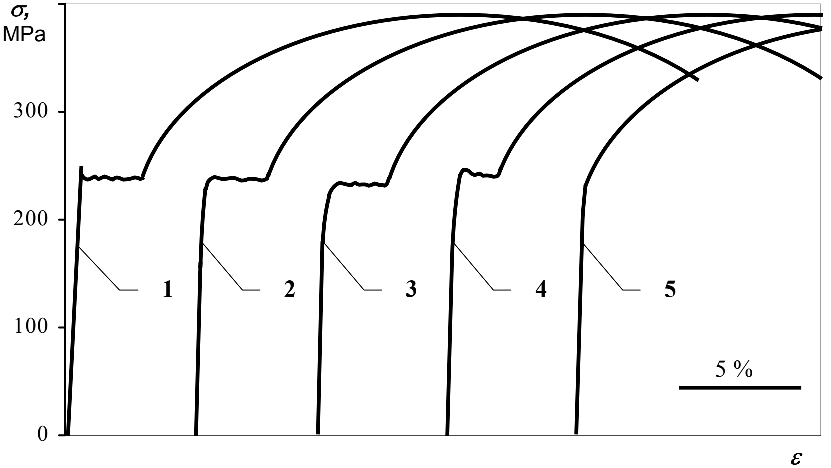


Fig. 7. Change of yield plateau form for the specimens subjected to repeated tension ($\sigma = 230$ MPa) for definite number cycles before the monotonic tension test: 1 – annealed specimen, – after 10^2 cycles, 3 – after 8×10^2 cycles, 4 – after 3×10^3 cycles, 5 – after 1.8×10^4 cycles

The load resulting yield plateau remains without changes. Disappearance of the yield plateau is accompanied by the decrease of proportionality limit. But, when, in course of cyclic loading, Luders deformation front passes entire specimen length, proportionality limit increases again up to approximate initial value.

Experimental data of Luders deformation front propagation kinetics at repeated tension at various loads are presented in Figs. 8 and 9. Curve 2 of the Fig. 9 corresponds to the start of Luders deformation and the end of incubation, when there are no yield plateau length changes. Curve 3 corresponds to the end of the process. Such incubation for the first time was noticed for metals, having yield plateau and fatigue limit, during investigation of the yield plateau change kinetics at tension-compression fatigue tests. Differently that in tension-compression, in our case (repeated tension) passing period of Luders deformation front is more prolonged.

It was revealed that at repeated tension, after some incubation, macroscopic deformation starts at the stress even smaller than fatigue limit. At stresses lower than fatigue limit (but not lower than 140 MPa), Luders deformation front at fatigue loading does not pass through all working part of the specimen, but it stops at certain time. Quantitative data of Luders deformation front propagation kinetics at repeated stress lower than fatigue limit presented in Fig. 9. For example, at cyclic stress 180 MPa, i.e. at 40 MPa lower than fatigue limit, Luders deformation front occupies only about 20 % of the specimen surface. At stress equal to 140 MPa macroscopic deformation was not noticed at all. Analysis of the yield plateau form and length kinetics enables to understand processes, taking place in the metals with yield plateau at cyclic loading.

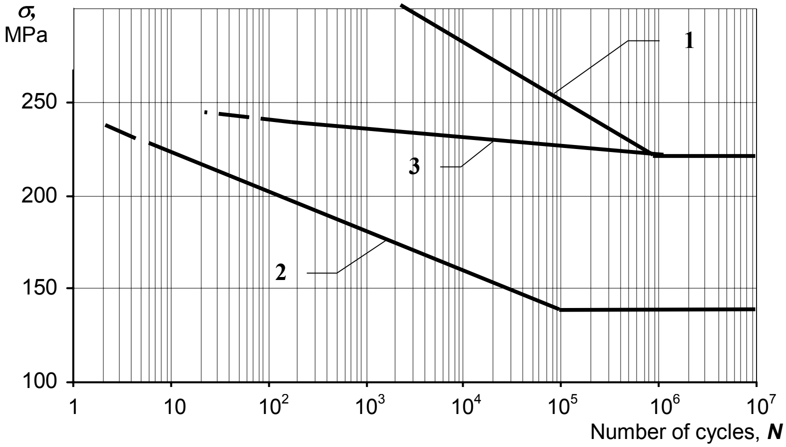


Fig 8. Propagation of Luders deformation front at cyclic loading: 1 – fatigue curve, 2 – line of Luders deformation propagation start, 3 – line of the end of Luders deformation front propagation

At the stresses, equal to fatigue limit, macroscopic deformation in the metal surface layers starts from the very first loading cycle. This deformation noticeably strengthens metal surface layer (about one grain size) only during all the incubation period. Strengthening of the surface layer happens due to dislocation density increase and dynamic deformation ageing. Only negligibly small microplastic deformation takes place in the entire specimen cross-section.

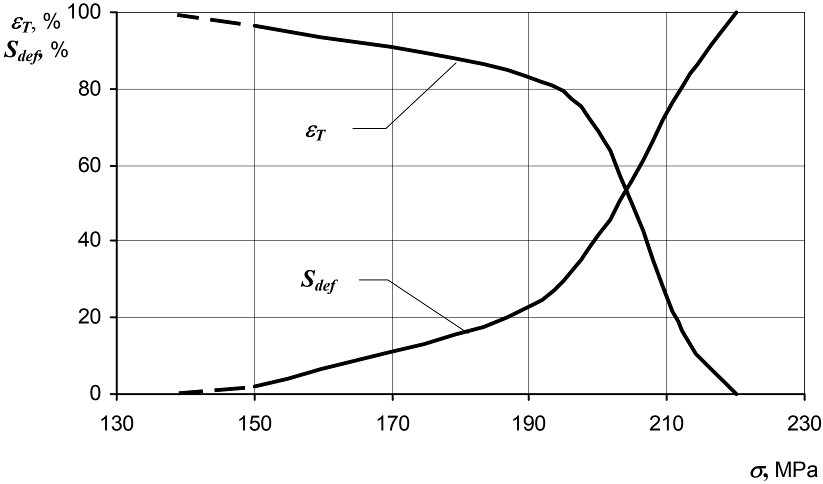


Fig. 9. Kinetics of macroscopic deformation accumulation at stress, smaller than fatigue limit: ε_T – length of yield plateau after cycling loading, S_{def} – area of Luders deformation front propagation on the working surface of the specimen

Due to both plastic deformation diversity in the metal surface and inner layers, and dynamic deformation ageing processes, in the end of incubation period formation of stringer metal surface layer is finished. At certain number of cycles, corresponding to the end of incubation period, the local breakthrough of the surface layer takes place and macroscopic deformation in the entire specimen cross-section starts. Further cyclic deformation results passing of Luders deformation front along the all working length of the specimen. Kinetics of Luders deformation front passing at repeated tension is the same as at monotonic tension. However in surface layers the increased dislocation density in comparison with dislocation density in the inner metal layers is preserved. It is because larger deformation of surface layer grains and because the surface layers generate more dislocations.

At further cyclic deformation, when stress approaches fatigue limit, macroscopic strain accumulation in the whole specimen volume was not noticed, but in the surface metal layers remains higher dislocation density. Intensive dynamic deformation ageing processes take place as well.

When the basic number of cycles is achieved, in the surface layer the uniformly strengthened surface layer with increased density of blocked dislocations is formed. In this case, the microcracks can initiate in the middle of separate grains of the surface layer. Further propagation of the cracks was not noticed even at the highest numbers of cycles. This critical stress, which results formation of the strengthened surface layer, corresponds to the material’s fatigue limit.

Thus, based on the presented model, explanation of the fatigue limit is related to formation of the strengthened surface layer (approximately equal to the grain size), at any cyclic load, does no matter, if it is torsion, tension-compression or others. The fatigue limit corresponds to such stress value, which does not develop critical microcracks in the strengthened surface layer. Such material surface layer is characterized by higher strength in comparison with inner layers. This layer serves as a barrier for dislocations going out from material inner layers, and in this way it blocks formation of irreversible damage.

Fatigue limit of the annealed low-carbon steel sometimes is a little higher than yield strength at monotonic tension. During cyclic loading at the stress equal to fatigue limit, intensive dynamic strain ageing is blocking the dislocations. Higher dislocations density remains in the surface layers of the metal, and this circumstance retards formation of fatigue cracks of critical length.

The results of the investigation explains formation of endurance limit for deformation ageing BCC metals and alloys. In these metals, formation of uniformly strengthened surface layer is conditioned by the circumstance that plastic deformation at both monotonic and cyclic loading starts to proceed in the thick surface layer, which depth equals to one – two grain size. It is influenced by two factors: great number of sliding systems and deformation ageing. Investigations carried out show that plastic deformation in the surface layer is going on in similar way at both monotonic and cyclic loading conditions.

In order to clear up deformation peculiarities more precisely at monotonic and cyclic loading of low-carbon steel, disloacation structure changes in both surface and internal metal layers were investigated. The dislocation structure was investigated by use of transmission electron microscope *IEM-7A*.

Observation of initial dislocation structure of the steel revealed single dislocations on the metal surface, inside of grains and on the borders between them.

Deformation inside the specimen and on it’s surface is going on unevenly, and maximum nonuniformity is when upper yield strength (yield point) is achieved. Deformation up to the yield plateau results the change of metals dislocation structure. Dislocation density increase on the grain borders. This is going on on the specimen surface as well as inside the specimen, but dislocation density on the surface is higher than that inside of the specimen. Dislocation density increase inside the grains is insignificant.

In the yield plateau (at strain equal to 0.7 %) dislocation density further increases and dislocations start to pass intensively from grain boundaries to grain bodies. But dislocation density on the specimen surface stays higher than that in the inner layers.

Investigation of the dislocation structure at monotonic and cyclic deformation revealed some common features of the structure change. When microscopic deformation front moves, dislocation density on the grain boundaries immediately increases inside the metal and on it’s surface. Dislocations are accumulated around impurities. But in the surface layer amount of dislocations is in no comparison higher.

Very important similarity of dislocation structure of the cyclic and monotonic yield phase is formation of grained dislocation structure. It confirms the fact that during cyclic and monotonic loading the deformation processes are similar.

Formation of dislocation structures at monotonic and cyclic loading of low-carbon steel was investigated using multifractal parametrization. Quantitative characteristics were obtained by use of original multifractal parametrization method. Initial processing of the dislocation structure photos was performed approximation them by digital graphic images by use of computer software *Adobe Photoshop 6*. Approximated view is reflected on the pixels matrix, where every pixel has corresponding colour characteristic. In our case, for an elementary particle (pixel) reflecting dislocation structure (dark background on a photo) value “1” was ascribed, and for the background – value “0”. Computerized calculations were carried out using software *MFRDrom*. Traditinional multifractal characteristics $f(\alpha)$ and $D(q)$ spectra, as generalized Reni dimensions, were calculated during selection q values from the interval [–100; 100] and apportionment dials 2, 3, 4, 6, 8, 12, 16, 24, 32, 48, 64, 128, 192, 256, 384 by use of scale selection schemes.

Everyone view of investigated dislocation structure was obtained as a result of calculation from six – seven square (768×768 pixels size) parts “cut out” of the photo, in order to get mean values of multifractal characteristics for every structure under investigation. Such square part corresponded to approximately 1.5 μm^2 area of a real foil.

Based on our theoretical and experimental investigations it is assumed that for quantitative parametrization the following characteristics should be used: generalized Reni dimension D_q at positive values of $q = \max$ (in our case $q_{max} = 100$), and effective quantitative characteristics of uniformity f_q and texture Δ_q, at positive values of $q = \max$. Characteristic D_q supplies certain quantitative information related to thermodynamic formation conditions of the structure under investigation. In some cases it may be asserted that large D_q values (when $q > 1$) correspond to large entropy values. Value D_q may be used as an effective mean to recognize material structures, which very difficult or imposible to identify by traditional quantitative methods. Thus, the possibility arise to recognize structures, obtained at the same conditions, and to define connections among structures formation conditions. Value Δ_q reflects texture and orderliness, and symmetry damage of all structure configuration subjected to investigation. Increase of Δ_q (according to module) shows that amount of periodical components of the structure is growing, the degree of symmetry damage is decreasing and structure becomes more textural (more ordered). Degree of structure uniformity f_q is considered not like traditional characteristic of the structure view, but like character index of unit elements distribution, containing all the structure, in the Euclidian space. Higher value of f_q corresponds to more uniform structure.

Because multifractal analysis considers distribution of some values in the geometrical medium, therefore, in our case, distribution of metal dislocation structure unit elements in plane was investigated. Photos of dislocations were approximated and by use of computer software main multifractal characteristics and strains (in case of monotonic tension) and number of cycles (in case of cyclic loading) dependencies were computed. Having these dependencies, it is possible to describe precisely regularities of dislocation structures evolution.

It was noted that there is no linear relationship between both uniformity characteristic f_{100} and deformation (number of cycles) as well as between texture characteristic Δ_{100} and deformation (number of cycles). But large correlation coefficients among D_{100} and deformation ε (in case of monotonic tension $r = 0.97019$) as well as among D_{100} and the number of cycles N (in case of cyclic loading $r = 0.91567$) allow us to assume that quantitative structure characteristics obtained, precisely enough reflect formation of dislocation structure.

Small amount of dislocations was noticed in annealed specimens. At monotonic tension increase of a deformation results more uniform structure, but when the deformation reaches yield plateau and dislocation density clearly increases, this characteristic begin to decrease. The texturity of the structure, which decreases at the beginning, with increase of deformation stays stable.

Evolution of dislocation structure is going on in a similar manner at cyclic loading too. Growth of the number of loading cycles results more uniform structure, but when the certain number of cycles is achieved, this characteristics falls down. From this moment texturity of the structure starts to increase. The dislocation structure becomes more and more ordered.

Very often traditional quantitative characteristics of a material structure may not be related to the factors, which influence change of the material structure. But use of multifractal parametrization and introduction of such quantitative characteristics as uniformity f_q and texturity Δ_q, enables to analyse structure formation at conditions more precisely.

Quantitative evolution of low-carbon steel dislocation structures, which were formed at monotonic and cyclic loading, revealed that dislocation structure evolution on the surface is identical at monotonic and cyclic deformation of the metal. Small differences, discovered as a result of this evolution by the multifractal parametrization method, may be explained by the different rate of deformation process.

Conclusions

1. It is determined that hardened layer depth of middle-carbon steel can be measured by non-destructive testing. For this purpose original method based on Barkhauzen effect was developed.
2. New perspective methodology of fractal parametrization is applied to investigation of the relationship between material properties and their structure. It is determined that evolution of dislocation structure in low-carbon steel specimens at both monotonic tension and cyclic deformation is similar, and plastic deformation process at both loading modes in the metal surface layer is analogous.
3. At monotonic tension and cyclic deformation of low-carbon and middle-carbon steel (metal with BCC lattice), the dislocations first of all are activated in the surface layer, therefore deformation processes going on in 1 – 2 grain depth surpass analogical processes in the inner layer of the metal. Increase of the dislocation amount in the surface layer is noticed on the stage of microyield, but in the internal layer it is noticed only on the yield stage.
4. Influence of surface layer on the Haasen-Kelly effect in middle-carbon steel is investigated. It is discovered that yield point formation is related to the strengthened surface layer of 1 – 2 grains depth, which is formed during deformation process. The yield point disappears, if the strengthened layer is removed, independently on the degree of prestrain.
5. It is proved by the tests that small strain hardening (to 2.0 %) of middle-carbon steel and duralumin specimens surface layer changes material’s characteristics and the form of monotonic tension curve. The yield plateau in the tension curve for middle-carbon steel disappears at 0.95 % surface layer strain hardening of the specimen.
6. Surface strengthening increases fatigue strength of middle-carbon steel. Most effective fatigue strength increase (up to 8 %) is achieved at 0.3 mm – 0.4 mm depth surface hardening.
7. Ageing of 10 % strained middle-carbon specimens in the stressed state results in decrease of relative elongation from 24 % to 17 %.
8. Length of the yield plateau depends on cyclic prestrain. At cyclic straining of a steel (230 MPa stress) with following monotonic tension, the yield plateau disappears after 1.8×10^4 cycles.
9. The data obtained can be used in the industry for metal treatment technological regimes selection, for improvement of mechanical, technological and operation properties of machine parts and structures, for reduction their cost and increase of their lifetime.

List of publications

Articles

In the reviewed International editions

1. Čiuplys A., Vilys J., Čiuplys V., Kvedaras V. Plastic flow of BCC metals at monotonous static and dynamic cyclic loading // Proceedings of the Estonian Academy of Sciences. Engineering. ISSN 1406-0175. Tallinn: Estonian Academy Publishers, 2003. Vol. 9, n. 4, p. 252-260.

Articles

In the reviewed Lithuanian editions

2. Vilys J., Čiuplys V., Čiuplys A., Kvedaras V. Influence of Surface Layer Squeezing on the Mechanical Properties of Metals // Materials science (Medžiagotyra). ISSN 1392-1320. Kaunas: Technologija, 2002. Vol. 8, n. 1, p. 14-19.
3. Kvedaras V., Vilys J., Čiuplys V., Čiuplys A. Surface Treatments for Improvement of Steel Static and Fatigue Strength // Materials science (Medžiagotyra). ISSN 1392-1320. Kaunas: Technologija, 2002. Vol. 8, n. 4, p. 380-383.
4. Kvedaras V., Vilys J., Čiuplys A. Plieno eksploatacinių savybių gerinimas taikant paviršinio sluoksnio stiprinimo būdus // Jūra ir aplinka. ISSN1392-785X. Klaipėda: Klaipėdos universitetas, 2002, nr. 1(6), p. 34-38.
5. Vilys J., Čiuplys V., Čiuplys A., Kvedaras V. Influence of Work Hardened Layer Thickness on the Mechanical Properties of Metals // Materials science (Medžiagotyra). ISSN 1392-1320. Kaunas: Technologija, 2003. Vol. 9, n. 1, p. 3-8.

Articles

Proceedings of National and International conferences

6. Čiuplys V., Vilys J., Čiuplys A., Kvedaras V. Improvement of a Steel Fatigue Strength by Fatigue Crack Growth Retardation // Materials Engineering-99. Materials of VIII-th International Baltic Conference. Kaunas: Technologija, 1999, p. 77-81.
7. Čiuplys V., Vilys J., Čiuplys A., Kvedaras V. Influence of Surface Hardening on the Spreading of Fatigue Crack // International DAAAM. Proceedings of the 2nd International Conference, 27-29th April, 2000. ISBN 9985-894-21-9. Tallinn: Tallinn Technical University, 2000, p. 251-254.

8. Vilys J., Čiuplys V., Čiuplys A., Motiejūnas D., Kvedaras V. Deformacijos ypatumai metalo paviršiniame sluoksnyje veikiant statinėms apkrovoms // Mechaninė technologija XXIX. Mokslo darbai. ISSN 0204-2053. Kaunas: Technologija, 2001, p. 54-59.
9. Kvedaras V., Vilys V., Čiuplys A. Plieno statinio ir ciklinio stiprumo pagerinimas panaudojant paviršinius stiprinimo būdus // Technologijos mokslo darbai vakarų Lietuvoje III. ISBN 9955-456-56-6. Klaipėda: Klaipėdos universiteto leidykla, 2002, p. 34-36.
10. Vilys J., Čiuplys V., Čiuplys A., Kvedaras V. Sukietinto sluoksnio storio įtaka metalų mechaninėms savybėms // Mechanika – 2002. Tarptautinės konferencijos pranešimų medžiaga. ISBN 9955-09-160-6. Kaunas: Technologija, 2002, p. 245-250.
11. Kvedaras V., Vilys J., Čiuplys V., Čiuplys A. Paviršinio sustiprinimo įtaka nuovargio lūžio struktūrai // Mechanika – 2003. Tarptautinės konferencijos pranešimų medžiaga. ISBN 9955-09-404-4. Kaunas: Technologija, 2003, p. 173-178.
12. Vilys J., Čiuplys V., Čiuplys A., Nikonovas A., Kvedaras V. Sendinimo prie įvairių apkrovų įtaka plieno 35ГС mechaninėms savybėms // Mechanika – 2003. Tarptautinės konferencijos pranešimų medžiaga. ISBN 9955-09-404-4. Kaunas: Technologija, 2003, p. 234-239.
13. Čiuplys A., Vilys J., Čiuplys V., Kvedaras V. Plastic flow of BCC metals at static and cyclic deformation // Abstracts of the 12th International Baltic Conference Engineering Materials & Tribology Baltmattrib – 2003. ISBN 9985-59-383-9. Tallinn: Tallinn Technical University, 2003, p. 46.
14. Vilys J., Čiuplys A., Čiuplys V., Kvedaras V., Jankovič O. Takumo aikštelės kitimo kinetika ciklinio apkrovimo metu // Mechanika – 2004. Tarptautinės konferencijos pranešimų medžiaga. ISBN 9955-09-630-6. Kaunas: Technologija, 2004, p. 522-527.
15. Vilys J., Čiuplys A., Čiuplys V. Galimybės panaudoti fraktalinę parametrizaciją medžiagotyroje // Mechanika – 2004. Tarptautinės konferencijos pranešimų medžiaga. ISBN 9955-09-630-6. Kaunas: Technologija, 2004, p. 528-534.
16. Vilys J., Čiuplys A., Čiuplys V., Kvedaras V. Influence of the Superficial Layer on Resistance to Plastic Deformations of Steel // Proceedings of the XIII-th International Baltic Conference Engineering Materials & Tribology *2004. Riga: Riga Technical University, 2004. p. 68-71.
17. Vilys J., Čiuplys A., Čiuplys V. Use of Fractal Parametrization in Materials Science // Proceedings of the XIII-th International Baltic Conference Engineering Materials & Tribology *2004. Riga: Riga Technical University, 2004. p. 158-160.

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DEFORMUOTO PAVIRŠINIO SLUOKSNIO ĮTAKA ELASTINĖMS METALŲ SAVYBĖMS

Reziumė

Šio darbo tikslas buvo išsamiai ištirti procesus, vykstančius metalo paviršiniame sluoksnyje įvairiomis apkrovimo sąlygomis. Tyrimai buvo atliekami su dviejų rūšių plienu ir duraliuminiu. Darbas susideda iš įvado, literatūros apžvalgos, tyrimo metodikos, eksperimentinės dalies. Darbo pabaigoje pateikiami gauti rezultatai ir išvados.

Pirmajame skyriuje, literatūros apžvalgoje, pateikta darbų apie metalų ir jų lydinių plastinės deformacijos ypatumus statinio ir ciklinio apkrovimo metu bei paviršinio sluoksnio įtakos šiems procesams apžvalga. Literatūros duomenų analizė parodė, kad šiuo metu nėra bendros nuomonės apie paviršinio sluoksnio elgseną plastinės deformacijos metu. Vieni autoriai teigia, kad plastiškai deformuojant metalą paviršinis sluoksnis sustiprėja labiau nei vidinis sluoksnis, o kiti – kad susilpnėja. Tačiau dauguma autorių sutinka, kad paviršinis sluoksnis turi didelę įtaką bendram plastinės deformacijos procesui.

Antrajame skyriuje, tyrimų metodikoje, aprašyti tyrimams naudoti įrenginiai ir priemonės. Metalų mechaninės savybės buvo nustatomos statiniais tempimo ir daugiacikliais nuovargio bandymais. Apvalių bandinių paviršiniam sluoksniui kietinti buvo pagamintas specialus įrenginys. Pateikta nauja bandinių sukietinto sluoksnio gylio nustatymo metodika, leidžianti nesuardžius bandinio nustatyti šį gylį panaudojant magnetinį Barkhauzeno triukšmą. Dislokacinei struktūrai pačiame bandinio paviršiuje arba bet kuriame norimame gylyje tirti sukurta folijų gamybos metodika. Kiekybiniam dislokacinių struktūrų įvertinimui buvo pritaikyta nauja multifraktalinės parametrizacijos metodika.

Multifraktalinėms charakteristikoms skaičiuoti panaudota kompiuterinė programa *MFRDrom*.

Trečiajame skyriuje, eksperimentinėje dalyje, aprašyta eksperimentų atlikimo eiga, gauti rezultatai bei jų aptarimas. Eksperimentiškai įrodyta, kad nedideliu laipsniu (iki 2,0 %) apspaudus vidutinio anglingumo plieno ir duraliuminio bandinių paviršinį sluoksnį, labai pakinta metalo mechaninės savybės ir statinio tempimo kreivės forma. Vidutinio anglingumo plieno takumo aikštelė tempimo kreivėje išnyksta dėl bandinių paviršinio sluoksnio apspaudimo 0,95 %. Paviršinė plastinė deformacija didina plieno ciklinį atsparumą. Vidutinio anglingumo plieno atsparumas nuovargiui efektyviausiai padidėja tada, kai sustiprinančio sluoksnio gylis siekia 0,3 – 0,4 mm. Sendinant įtemptą plieną, sumažėja jo santykinis pailgėjimas ir padidėja trapumas. Labiausiai plieno plastiškumas sumažėja jį sendinant, kai apkrovos artimos stiprumo ribai.

Išnagrinėtas dislokacinės struktūros kitimas paviršiniame ir vidiniame metalo sluoksnyje statinio ir ciklinio apkrovimo metu. Deformuojant mažaanglį ir vidutinio anglingumo plieną, dislokacijos pradžioje aktyvuojamos paviršiniame sluoksnyje, todėl deformaciniai procesai 1 – 2 grūdelių gylyje paviršiniame sluoksnyje pralenkia analogiškus procesus metalo vidiniame sluoksnyje. Dislokacijų tankis labiausiai didėja grūdelių ribose ir apie priemaišas, susidaro grūdelinė dislokacinė struktūra. Abiem apkrovimo atvejais dislokacijų tankis paviršiniame sluoksnyje visose deformavimo stadijose būna didesnis negu vidiniame sluoksnyje. Taikant multifraktalinę parametrizaciją nustatyta, kad dislokacinės struktūros kitimas paviršiniame ir vidiniame mažaanglio plieno bandinių sluoksnyje abiem apkrovimo atvejais yra panaši, todėl plastinė deformacija metalo paviršiniame sluoksnyje vyksta panašiai tiek statinio, tiek ciklinio apkrovimo metu.

Gauti rezultatai gali būti panaudoti gamyboje, parenkant technologinius metalo apdirbimo režimus, gerinant mechanines, technologines bei eksploatacines mašinų detalių ir konstrukcijų savybes, mažinant jų savikainą ir didinant ilgaamžiškumą.

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