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Use of the Ion-Plasma Treatment for Improving the Structural Strength of Items

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The paper shows that the ion bombardment (IB) by low-energy ions essentially influences the behavior of a specimen under tension testing changing strength and ductility of the item as a whole though the same properties of metal remain in its core. IB also increases fatigue strength and can be used for improving the ductility of sheet steels. This treatment is especially effective for items with technological stress concentrators and is recommended as a very effective and simple method of improving their structural strength. The phenomenon is explained by surface nanostructuring during ion bombardment.

Keywords: Structural strength, Surface nanostructuring, Ion-plasma treatment, Ion bombardment, Low-energy ions, Nondislocation mechanism of plastic deformation.

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1. INTRODUCTION

It is known that the behavior of outer and inner layers of metal under loading is different even without any special surface treatment [1], first of all due to uncompensated surface atomic bindings. At present the surface layer of items is considered as an independent subsystem crucially affecting the item behavior under deformation and its properties [2].

It is possible to change the surface state of items by different methods: surface quenching, thermochemical treatment, severe plastic deformation, power ultrasonic impact action, application of different coatings, including ion-plasma ones. Such treatments not only modify the properties of the surface layer but also can radically change the under-deformation behavior and the mechanical characteristics of an item as a whole.

Earlier it has been shown that the most efficient method of influencing the behavior of an item under deformation and its properties is ion-plasma treatment (IPT) [3]. As a rule, IPT is used for obtaining coatings with special properties: high hardness, wear resistance, corrosion resistance and so on. This paper demonstrates another aspect of this treatment – the possibility to influence the properties of an item as a whole using only ion bombardment (IB), without coating deposition.

The aim of the paper is to demonstrate that the IB without any coating deposition sufficiently increases the values of strength and ductility of items not only under static, but also under cycling loading and can be used as a separate treatment assuring the uniquely high structural strength of items and deformability of steels.

2. DESCRIPTION OF THE OBJECTS AND INVESTIGATION METHODS

In this research the standard specimens for tensile (5 and 10 mm in diameter) and fatigue tests (10 mm in diameter) were used. Tensile tests were carried out on the specimens of structural low- and medium-carbon steels (18CrMnTi, 20Cr, 40CrNi, initial heat treatment - improving), fatigue tests – on the steel 40Cr (initial heat treatment - improving) and spring steel 60Mn (initial heat treatment – quenching with medium-temperature tempering). The properties of sheet metal were determined on the flat specimens of steel 20 after annealing.

The specimens were tested after grinding (which corresponds to the standard requirement for tensile tests), polishing (which corresponds to the standard requirement for fatigue tests) and ion-plasma treatment (IPT). This made it possible to estimate the role of the surface state in the specimen behavior during testing and its effect on the properties of the article as a whole. For IPT the mechanical characteristics were determined after both stages of the process – after IB without coating deposition and after IB with subsequent TiN deposition.

IPT was performed by low-energy ions of Ti (1-3 keV) in argon, TiN deposition – in the atmosphere of nitrogen. The main condition during these processes was to prevent the specimen heating above the previous tempering temperature which could result in softening of the metal.

The following experimental methods were used: measuring of microhardness and nanohardness, estimation of surface roughness, X-ray and microspectral analysis, electron microscopy.

3. RESULTS AND DISCUSSION

Tension tests showed that the state of an item surface has a very strong influence on its mechanical properties. For the specimens of steel 18CrMnTi after polishing ultimate strength σ_u increases by 9 %, yield strength $\sigma_{0,2}$ by 22 %, after IB - by 17 % and 34 % and after TiN deposition – by 24 % and 40 %, respectively, compared to the grinded specimens. It is important to note that elongation δ is preserved at the sufficient level (15-16 % compared to 18 % in the initial state), and the reduction in area ψ (a more representative characteristic which determines item reliability) after IB even increases – from 64 % to 67 %. Such strength growth without a loss of ductility cannot be achieved by any of the known volume methods of strengthening changing the structure in the whole cross-section of items. As a rule, the maximum increase of the strength which is not accompanied by embrittlement does not exceed 15 %. It should be particularly emphasized that it is precisely the stage of IB that plays a major role in this effect and gives the most part of common strengthening [3].

The results of the fatigue tests are shown in Table 1.

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Table 1 – Cycle service life of specimens after different treatments

Steel and heat treatment	Loading stress, MPa	Number of cycles before fracture
40Cr, improving	380	297600 (destroyed)
40Cr, improving + IB	430	453840 (destroyed)
60Mn, quenching, medium-temperature tempering	380	937440 (destroyed)
60Mn, quenching, medium-temperature tempering, + IB	548	11160000 (undestroyed)

Table 1 demonstrates that IB sufficiently increases the cycle service life for both analyzed steels. If the specimen of steel 40Cr in the initial state was destroyed under 380 MPa, after IB it was destroyed only under loading stress of 430 MPa, and in spite of the higher stress level the number of cycles before fracture increased by 1,5 times. The specimen of steel 60Mn in the initial state was destroyed under 380 MPa, but after IB it was not destroyed even under 548 MPa, which is 44 % higher and is the maximum value for specimens with $d = 10$ mm. So we can conclude that IB not only improves the structural strength of items under static loadings but also substantially increases their resistance to fatigue fracture.

It is necessary to remind that according to the standard requirements specimens for fatigue testing are polished since surface roughness dramatically effects the results. IB increases the roughness R_a of previously polished specimens from 0,12 to 0,16 μm, but despite this the cycle service life remarkably rises after such treatment.

For the flat specimens of steel 20 very sufficient increase of ductility after IB was observed. Fig. 1 shows the stress-strain dependences for this steel before and after IB. The curves are built in the same scale. This allows to compare them and to draw a conclusion about the properties changing.

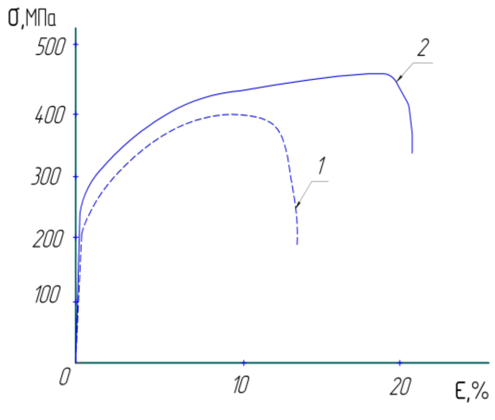

Fig. 1 – Stress-strain curves for the flat specimens of steel 20: 1 – initial state (annealing); 2 – annealing + IB

The strength and ductile characteristics are summarized in Table 2. This table also shows the Vickers hardness.

From these data we can conclude that after IB σ_u and $\sigma_{0,2}$ increase by 4 and 14 %, respectively, but in spite of this the reduction in area ψ also greatly increases - by 160 % (!), elongation δ - by 76 % and the uniform elongation δ_u by 81 %. Such unique increase of ductility combined with simultaneous rise of strength has never been achieved before by any known heat treatment.

Table 2 – Mechanical properties of the flat specimens (steel 20) after different treatment: 1 - initial state (annealing); 2 – annealing and IB

№	σ_u, MPa	$\sigma_{0.2}$, MPa	δ, %	δ_u, %	ψ, %	HV_5
1	390	220	13	11	15	130-133
2	425	250	23	20	39	125-132

The above data give the basis to affirm that IB allows to design items with unique properties, combining very high strength, ductility, reliability, cyclic durability. Such characteristics are reached after short-time (about 2 min) action of low-energy Ti ions on item surface. In such conditions ions of Ti penetrate to the depth no more than 1 μm, what was shown by X-ray microspectrum analysis [3]. The measurements of hardness and microhardness across the specimen section proved that it does not change in the inner layers. So we can conclude that the deep strengthening by IB in our case does not take place. This is confirmed also for the flat specimens. As Table 2 shows hardness HV5 is practically the same for both states – before and after IB. Measuring the imprint diagonal allows to estimate the depth of indenter penetration under such loading. According to our data it is about 40 μm. From this we can conclude that at this depth the hardness is the same in both specimens. If during IB surface hardness increases, under loading ~ 50 N this strengthened layer is squeezed through by indenter and we register the same hardness.

The presence of the strengthened surface layer after IB was deteched by nanoindentation [4]. Its thickness is about 50 nm. On the very surface nanohardness increases as compared to the initial state from 7,8 to 14 GPa but it decreases sharply and at the depth of 50 nm reaches about 5 GPa.

It is important to emphasize that the surface hardness is not the decisive factor in strengthening after IPT. After deposition of TiN coating surface nanohardness increases to 21 GPa (instead of 14 after IB), but it adds only ~ 5 – 6 % of strengthening to that obtained after IB.

The results of the presented experiments prove that the properties of specimen inner layers after IB do not change. The effect of exclusively high strength and ductility characteristics after IB is a result of special behavior of specimen under loading. We propose the following hypotheses for explaining this phenomenon.

During IB two processes take place. The first one is healing of surface imperfections due to the sputtering of the surface layer, decreasing the roughness, blunting cavities sharpness which, according to the Griffits theory, leads to the increase of fracture toughness. For IB defects healing is a known process and was confirmed by our experiments.

The second process is the formation of a nanocrystalline layer about 50 nm thick on the specimen surface which has been determined by nanohardness measuring.

We classify it as nanocrystalline since, according to the current views, the nanostructured materials include solids with structural elements (grains, particles, chemical inhomogeneous zones, layers of multilayer coatings and so on) less than 100 nm, under condition that they essentially affect their properties [5].

The phenomenon of mechanical properties increase by healing surface imperfection was described by academician A. Ioffe in 1920's. He discovered that tension of NaCl specimens in water resulted in the increase of σ_u, compared to tension in air, from 5 to 1600 MPa and this was accompanied by high ductility. The cause of changing properties was healing of small surface imperfections due to salt solution in water.

Conditions of our experiments differ from those of A. Ioffe. In the cited work deformation was performed in a medium which removed not only the initial surface imperfections but also those which emerged during tension and could form the strain concentrators and as consequently the specimen destruction. In our case the specimens were tested in air, that is, in conditions when the surface layer damaged under deformation (debris layer) could not be removed. Nevertheless a specimen, in spite of huge strengthening, remained ductile. In our opinion this can be explained exactly by the influence of nanostructured layer on a specimen behavior during deformation.

At present most of the scientists agree that the plastic deformation in nanostructures is performed by a nondislocation mechanism [5]. In such materials nanograin sliding and rotation modes assuring grain accommodation and stresses relaxation play the main role. During tension the deformation in surface nanostructured layer is performed by such mechanism which eliminates the stress concentrators appearing at the surface and the related embrittlement.

The hypothesis about the key role of surface layer in the behavior of an item during deformation fits the data obtained on the flat specimens which have very high surface-volume ratio S/V. For our case (the working part of the specimen is $97 \times 12{,}5 \times 1{,}2$ mm) this ratio is equal to 1,83 mm - 1. For comparison S / V of cylindrical tension test specimens by $d = 5$ mm is equal to 0,9, by 10 mm – to 0,44. So, this ratio for the flat specimen is two and four times as much as that of the cylindrical specimens, respectively. That is the reason why the role of the surface manifests itself so prominently for the flat specimens.

We propose IB as a very effective method of improving the structural strength of items, especially with technological stress concentrators, reliability, cyclic durability, exclusively high ductility. The use of this method for connecting rod bolts (steel 40 CrNi, improving) allows to increase the ultimate strength σ_u from 574 MPa to 970 MPa, $\sigma_{0,2}$ from 443 MPa to 815 MPa, that is by 69 % and 84 %, respectively, without embrittlement [6]. IB can be very effective for improving deformability of sheet steels designed for cold plastic deformation (extrusion, stamping, forming).

4. CONCLUSIONS

1. Ion bombardment without coating deposition is a very effective method of structural strength improving, increasing cyclic service life and reliability. For items without stress concentrators σ_u increases by 17 %, $\sigma_{0,2}$ by 34 %, with the stress concentrators – by 69 % and 84 %, respectively. It also can be successfully used for sufficient improvement steels deformability.

2. After IB the properties of metal in the core of an item are retained at the initial level. Zone of changed mechanical characteristics under the short-time action of low-energy ions does not exceed 1 μm. But such action cardinally influences the item behavior under loading and, as a result, the properties of an item as a whole.

3. The effect of reaching such extremely high structural strength and deformability is assured due to two processes – healing the surface imperfections (roughness decrease, blunting of cavities) and formation on the specimen surface of a nanocrystalline layer in which plastic deformation is performed by a nondislocation mechanism with nanograin sliding. This eliminates the stress concentrators appearance at the surface during deformation and the related embrittlement.

Использование ионно-плазменной обработки для повышения конструктивной прочности изделий

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Показано, что ионная бомбардировка (ИБ) низкоэнергетическими ионами очень существенно влияет на поведение образцов при растяжении, что приводит к изменению прочности и пластичности образца в целом, хотя свойства металла в сердцевине не меняются. ИБ также повышает сопротивление усталости и может быть использована для улучшения пластичности листовой стали. Эта обработка особенно эффективна для изделий с технологическими концентраторами напряжений и рекомендуется как очень эффективный и простой метод повышения конструктивной прочности изделий. Явление объяснено поверхностным наноструктурированием в процессе ионной бомбардировки.

Ключевые слова: конструктивная прочность, поверхностное наноструктурирование, ионно-плазменная обработка, ионная бомбардировка, низкоэнергетические ионы, недислокационный механизм пластической деформации.

Використання іонно-плазмової обробки для підвищення конструктивної міцності виробів

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Показано, що іонне бомбардування (ІБ) низкоенергетичними іонами суттєво впливає на поведінку зразків при розтягуванні, що приводить до зміни міцності та пластичності зразка в цілому, хоча властивості металу в серцевині не змінюються. ІБ також підвищує опір втомі і може бути використана для покращення пластичності листової сталі. Ця обробка особливо ефективна для виробів з технологічними концентраторами напружень и рекомендується як дуже ефективний і простий метод підвищення конструктивної міцності виробів. Явище пояснено поверхневим наноструктуруванням в процесі іонного бомбардування.

Ключові слова: конструктивна міцність, поверхневе наноструктурування, іонно-плазмова обробка, іонне бомбардування, низькоенергетичні іони, недислокаційний механізм пластичної деформації.

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