Rev.Adv.Mater.Sci. 8 (2004) 122-128

THE PHASE CONVERSION IN STAINLESS STEEL UNDER LSW PROCESSING

B.P.Kovalyuk[1], Yu.N.Nikiforov[1] and M.M.Nischenko[2]

[1]Ternopil Ivan Pul'uj State Technical University, 56 Ruska st., Ternopil, 46000, Ukraine
[2]Kurdyumov Institute of Metallophysics of Ukrainian National Academy of Sciences, 36 Vernadskogo Ave, Kyiv, Ukraine

Received: December 14, 2004

Abstract. There is a laser processing method known as LSW (laser shock waves in transparent condensed medium), which provides great surface compression and low plastic deformation and could be used for modification of material properties.
The influence of laser shock waves in transparent condensed medium on phase conversion in stainless steel X18H10T is studied by Mössbauer spectroscopy and electroresistance methods. The shock waves were generated by impact of nanosecond laser pulses with power density $q \sim 10^{13}$ W/m^2.
It is shown that shock waves passage in this material causes martensite conversion and increases corrosion stability. Austenite obtained in such a way has increased corrosion stability in liquid lithium in comparison with austenite obtained after conventional thermal treatment. The formation of austenite by the shock waves mechanism is connected with two rival action factors: great (2 GPa) compression and low ($\varepsilon \sim 0{,}001$) plastic deformation degree. The selective dissipation of LSW is the main factor which causes the cleaning of the grain border from the impurities and the homogenizing of structure.
A similar effect of homogenization and ordering after LSW-treatment was observed in IV – VI semiconductors.

1. INTRODUCTION

Shock waves are formed under the action of pulsed laser irradiation and are spread into the material as a result of high-quick (>10^{10} K/s) heating and intensive vaporization of the substance from the surface. Such conditions are created under irradiation of metals by the laser impulses of nanosecond range. High strain (σ) and short action time (<1 μs) of laser shock waves determine the pecularity of this method. They cause high speed of loading ($\geq 10^4$ s^{-1}) under small deformation ($\leq 0{,}001$) which prevents changes of the form in the irradiated material. The pecularities of such type irradiation of metals are comparatively small thermal depth (up to 5 μm) and sufficiently large (more three orders of magnitude) shock wave penetration ability [1]. Propagation of strain impulses in a metal in the form of shock waves causes the same changes in the microstructure and properties as the action of shock waves obtained by the other methods [2-6]. But the accuracy, effectiveness and safety of laser shock-wave processing are higher, compared with the methods which use explosives for similar purposes.

The very short duration of laser shocks and their low-destructive character provide new means of studying the kinetics of phase transitions [7].

Among FCC-metals stainless steel has the lowest value of packing defects [2]. While treating 18% Cr and 8% Ni stainless steels by the shock waves

Corresponding author: B.P.Kovalyuk, e-mail: kovalyukdan@yahoo.com

during 1 ms at deformation speed within $10^{-3}\div10^{3}$ s^{-1}, as a rule, formation of martensite is noticed, which is located in the areas of double zones crossing and forming sliding strips. When the pressure amplitude and pulse durability increases, volume portion of α–martensite increases too. Longer pulse durability, when thermal effects are not available, increases both the time of dislocation interaction and their length, which cause creation of more equilibrium dislocation clusters. It is shown in [2] that martensite mostly is not formed under shock impact loading (P = 25 GPa), if pulse time is less than 2 μs. At the same time when it is increased to 6 μs under the same range, it causes formation of a great amount of martensite.

Laser shock waves attenuation, decreasing of the maximum strain and the distance the wave passes in the metal, in particular, determines the depth of microstructure changes and properties. It should be in dependence on the energy dissipation mechanisms. If maximum shock wave strain is higher than dynamic yield limit (for Fe it is 0.79 GPa), its passage in the metal causes sufficient plastic deformation which leads to great increase of dislocation density. Transition of the energy by the shock waves within the material, mechanism of defects formation and their distribution within the depth were studied in the paper [1] by method of electron-positron annihilation. It was found that, after irradiation of the α–Fe surface by the powerful 50 ns laser pulses, an extensive region of three-dimensional defects appear, which are caused by the the shock waves generation in the material and its passing through it. It spreads far beyond (>4 mm) the zone of the surface thermal action (≤ 0,01 mm). Based on this, the authors came to the conclusion that the main mechanism of the shock wave attenuation, in this case, is defects initiation and migration.

The pecularity of dislocation formation under shock loading is their more homogenous distribution than under plastic deformation [2]. Their initiation is caused by the shear stresses which appear under single-axis deformation. They are spread with the subsonic speed in the shock wave front area.

According to the La-Shateler principle, phase transformation, decreasing with the volume, is thermodynamically more preferable under high compression, and, on the contrary, compression increasing does not lead to the phase transformation, which takes place when the volume increases. Thus, thermodynamically more preferable under high compression in X18H10T- steel is reverse $\alpha\rightarrow\gamma$ martensite transition, as γ–phase is of greater density as compared with α–phase. It is confirmed by the hydrostatic compression data, in particular, which demonstrates $\alpha\rightarrow\gamma$ transformation [2].

To get the reverse martensite transition it is necessary to exclude the conditions under which deformation martensite is formed. Decrease of deformation and, consequently, dislocation density and the volume portion of twins are possible due to the shorter compression pulses, generated in the metal, by the nanosecond laser pulses, in particular. In the future such treatment can be used for the synthesis of materials, increasing strength and corrosion resistance of metal, treatment of microcracks and micropores, structure homogenization, etc.

The effect of thermal treatment, plastic deformation and laser shock waves on the phase transformations in the stainless steel X18H10T are studied in the paper by the methods of gamma-resonance spectroscopy and electrical-resistance.

2. METHODS OF INVESTIGATION

Investigations were carried out by the electrical-resistance and gamma-resonance spectroscopy methods on the specimens of stainless steel X18H10T in the form of 25 μm thick foil. Annealing of the specimens in order to bring them in the austenite state were carried out at 1173K during 1 hour in vacuum ~10^{-5} Pa. Deformation of these specimens was done by rolling on the 25 mm thick mills.

Irradiation of the specimens was carried out with a Nd-laser. Irradiation pulse width was 50 ns, light flow power density – $0,4\cdot10^{13}$ W/m^2. To protect specimens from the plasma spray heating, taking place in such irradiation conditions, an 80 μm thick copper screen was used, which was in acoustic contact with the specimen. To increase compression pulse range, the value of which was checked by the special controllers, irradiation was carried out in the transparent condensed medium by the method used in [1]. In this case hydrodynamic expansion of plasma in the area which is in contact with the surface target and transparent condensed medium, forms a short compression pulse of 2 GPa.

Investigation of the phase state of X18H10T steel and its changes during thermal, laser or deformation treatment were carried out on the Mössbauer spectrometer at room temperature with a ^{57}Co source in Cr on the specimens in the form of 10, 25, and 50 μm thick foils. Electrical-resistance was measured by the four-probe method within the range 4.2÷1200K.

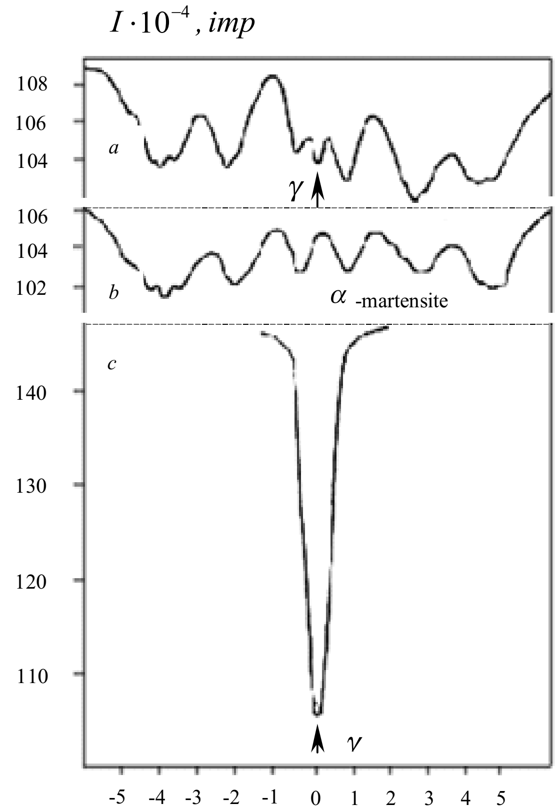

Fig. 1. Mössbauer absorption spectrums of X18H10T steel a) – after rolling to 25 μm, b) – after rolling to 10 μm, and c) – after roasting of the rolled specimen at 873K in argon.

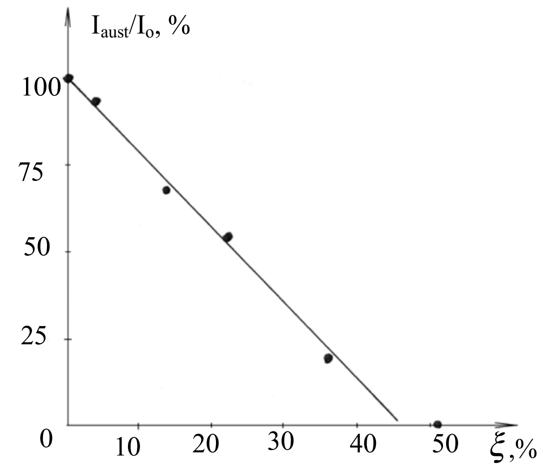

Fig. 2. Dependence of austenite amount changes (relative austenite spectrum square) on the level of the cold plastic deformation of the annealed steel X18H10T (25 μm).

To investigate corrosion resistance 25 μm thick specimens made of X18H10T, being in different conditions: 50% deformed after annealing by rolling, annealed at 1273K during 1 hour in vacuum 10^{-5} Pa and processed treated after annealing by the laser shock waves within the whole surface from one side, were kept in liquid lithium at 873K during 100 hours.

3. INVESTIGATION RESULTS

3.1. Effect of mechanical and thermal treatment

In Fig. 1 Mössbauer absorption spectrum of the specimen made of X18H10T steel, rolled to the thickness of 25 μm, is presented.

Complex splitted spectrum of the deformation martensite (α–phase) in ferromagnetic state and weak single line in the center (5% square from the total spectrum square) is noticed, which is obtained from the austenite (γ) paramagnetic phase. After rolling of the specimen up to 10 μm austenite phase is not found from the Mossbauer data (Fig. 1, b). Annealing of this specimen at 873K during 0.5 hour in the protective argon medium leads to α→γ transformation generally forming austenite, producing intensive paramagnetic line (Fig. 1c). Complex martensite spectrum structure (Figs. 1a and 1b) is caused by the superposition of sextets, which correspond to different iron atom configurations with different number of impurity atoms in the nearest surrounding.

Results of investigation of the cold plastic deformation effect on the phase composition of X18H10T steel, which was preliminary annealed in argon at 873K during 0.5 hour, are presented in Fig. 2.

25 μm thick specimen in annealed (original) state contains only one phase-austenite. After cold plastic deformation of this specimen by rolling, the amount of austenite decreases as a result of γ→α transformation (ε ≈ 50%), austenite disappears totally and only one phase remains – deformation martensite (α–phase).

3.2 Electrical-resistance

α→γ transformation kinetics has been investigated using the method of electrical-resistance. Measurements were carried out while heating specimens in vacuum from room temperature till 973K. In Fig. 3

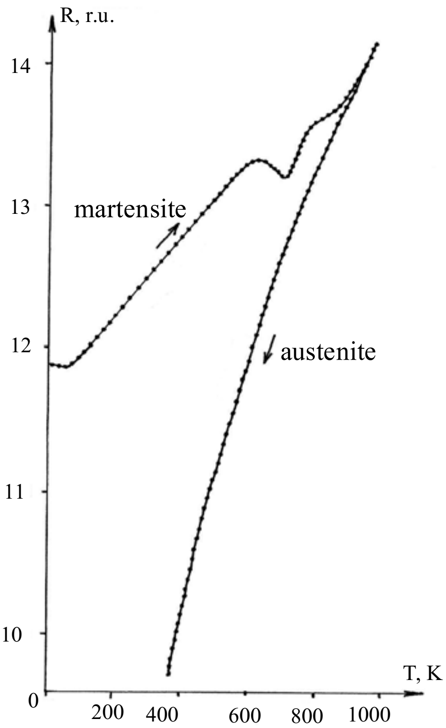

Fig. 3. Dependence of 10 μm thick specimens, made of X18H10T steel, electrical-resistance on the temperature.

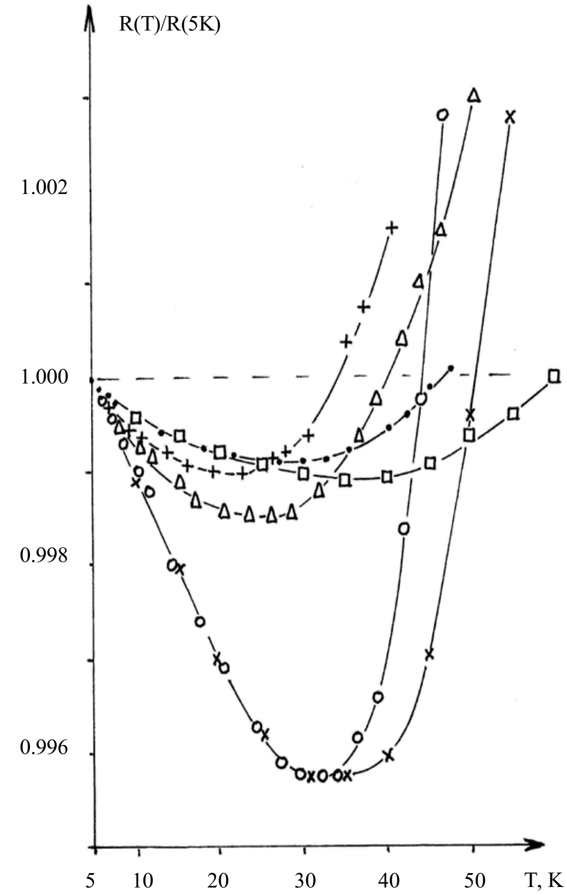

Fig. 4. Relative change of the electrical-resistance in the region of low temperature of the steel specimens after mechanical and thermal treatment. □ – rolled in hot state up to 10 mm, · – rolled in hot state up to 25 mm, Δ –annealed at 773K in vacuum $1.3 \cdot 10^{-5}$ Pa during 0.5 hour, × – annealed at 873K in argon during 0.5 hour, ○ – annealed at 1273K in vacuum $1.3 \cdot 10^{-5}$ Pa during 1 hour, + – annealed at 1573K in vacuum $1.3 \cdot 10^{-5}$ Pa during 1 hour.

R(*T*) curves for the 10 mm thick X18H10T steel specimens are presented.

Deviation from the smooth curve under heating starts at 613-633K, which shows the beginning of the $\alpha \rightarrow \gamma$ transformation.

Cooling of specimens heated to 973K leads to greater temperature dependence *R(T)*, which is caused by the lower number of dissipation centers for electrons and more homogeneous structure of austenite, as compared with that of martensite.

In the temperature range which is lower than that of 20-40K, a minimum in the *R(T)* curve is noticed.

In Fig. 4 *R(T)* curves, normalized to 1 at 5K for the steel specimens, being subject to different processing, are presented.

3.3. Shock waves effect on the phase transformations

After annealing of the specimen at 1173K during 1 hour in vacuum 10^{-5} Pa Mössbauer spectrum has the form of the single intensive line from the austenite γ–phase. Further cold rolling of the specimen leads to 50% formation of the martensite deformation (α–phase), which produces splitted Mössbauer spectrum (Fig. 5a). Pulsed laser treatment within the whole specimen surface, which contains 95% of martensite, leads to the appearance of the intensive single line in the spectrum center on the martensite lines ground, which does not show a complete $\alpha \rightarrow \gamma$ transformation (Fig. 5b), intensity of the central paramagnetic top of the austenite phase being rather increased. Pulsed laser treatment of the specimen with less deformation (ε=22%), which contained about 50% of martensite, laser shock wave treatment effect on γ-transformations increases

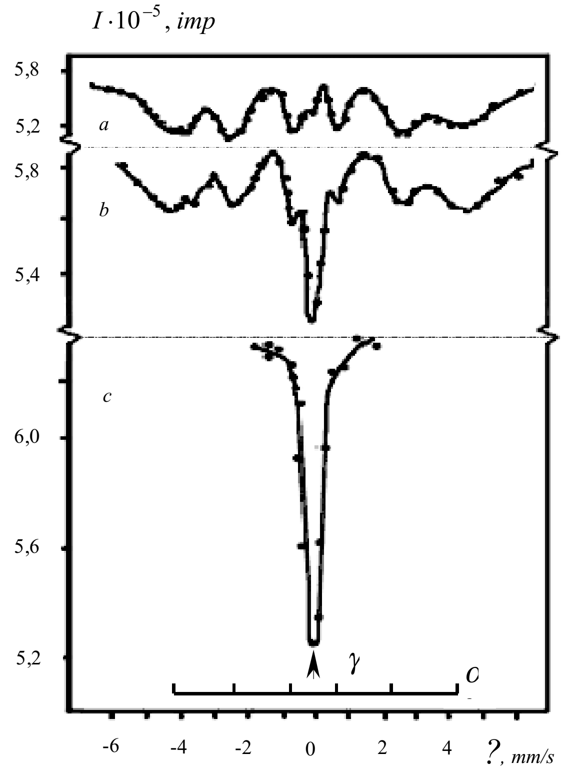

Fig. 5. Mössbauer spectrum for stainlees steel X18H10T a)- before, b), and c) – after LSW-treatment.

(Fig. 5c): amount of the produced austenite increases about to 100%. After irradiation of specimens, preliminary annealed at 873K, or 1273K, which contained only austenite γ–phase, martensite transformation does not take place and preserves austenite almost completely.

Reverse (α→γ) martensite transition, which is noticed under laser irradiation is caused by the shock compression. It can be predicted, that such processing of the material surface causes homogenization of the structure, cleaning of the grain borders from the impurities and raising corrosion resistance [8]. As our experiments dealing with the corrosion resistance showed, after keeping of the deformed specimen in the liquid lithium at 873K, martensite is transformed into austenite with unsufficient structure in the wings of the Mössbauer spectrum, which proves the formation of ferrite (α-phase) due to the selective dissolving of the steel components in the liquid lithium. Escape of only 2-3% of nickel from the austenite steel leads to γ→α transformation forming ferrite, which is easily identified by Mössbauer method with the appearance of the magnetic-splitted components. Structural changes were accompanied by the raise of the microhardness in 20%. Preliminary annealing of the specimen at 1273K sufficiently increased corrosion resistance of the steel in the liquid lithium and austenite line becomes practically structureless. It should be noticed, that all specimens except those processed by the laser shock wave, after keeping in the liquid lithium, had light-grey deposits on the surface. They are caused by the complex lithium under the same conditions of the specimen annealing at 1273K during 1 hour in the vacuum 10^{-5} Pa and further treated by the laser shock wave. A light-grey deposit on the surface is not found and in the Mossbauer spectrum only austenite line is noticed. On the specimens, treated by the laser shock wave, phase or gravimetric changes were not found. Inerease of the microhardness was not noticed either.

4. DISCUSSION

When a shock wave with a pressure ~2 GPa in the front passes through X18H10T steel, quasi-hydrostatic strains are greater than shear ones, and while lattice compression on the shock wave front the reverse (α→γ) martensite transition is done, which was noticed in the experiment. The necessary condition for its formation is the low degree of plastic deformation. That is why it is important to find this value. Direct methods of plastic deformation measuring are not available. However it is possible to use Smith model [9] to estimate residual (after shock loading) dislocation density and the degree of plastic deformation while the shock wave is passing through it. Dynamic deformation caused by the shock loading is found as

$$\varepsilon_{pl} = \frac{4}{3}\ln\frac{V}{V_0}.$$

It corresponds to the deformation sums, caused by the compression zones ($2/3\varepsilon_x$) and stretch ($2/3\varepsilon\alpha$); here $\varepsilon_x=\ln(V/V_0)$, V_0 – original volume, V – volume while shock wave passing.

To obtain quasi-hydrostatic compression of the material under one-axis loading in the case of the laser impulse action, plastic deformation must take place (ε_{pl}). Under hydrostatic compression beyond the Gugonio elasticity, relation [2] $\sigma_x=K\varepsilon_x$ is satisfied, where ε_x – strain in the direction parallel to the shock wave propagation, $K_{1/x}$ – all-side compression modulus, and x – compressibility.

As the compression under which the shock wave P=-σ_x is, so ε_x=cP. In the case of one-axis deformation under $dx/V_0=dV/V_0$, $\varepsilon=\chi dP$ (χ – compressibility). Then under dP=2 GPa and c of 10^{-12} Pa^{-1} level, the value of the relative deformation ε~0.001 will be obtained, and the speed of the plastic deformation $\dot{\varepsilon}$~10^4 s^{-1}.

As the experiment showed, such low degree of the plastic deformation of the stainless steel X18H10T does not cause the creation of the martensite deformation. According to the Meyers model, processing of the surface by the shock waves causes homogenization of the dislocation structure and cleaning of the grain borders from impurities. The latter, according to [10], can be caused by the migration of the interstitial atoms from the grain borders into its volume along the interstitial atom under the action of the excess forces pulse, obtained by the interstitial atom in the front of the shock wave.

These ideas allow to explain the reason of decreasing selective corrosion speed in liquid lithium at 873K (100 hours) of the stainless steel X18H10T treated along the whole surface by the laser shock waves as compared with the similar specimens, which were not treated by the laser pulses. Homogenization of the structure and cleaning of the grain borders from the impurities as a result of selective scattering of the shock waves on them and as a rule compression character of strains under laser shock wave action, are the factors, co-action of which is important for the raising of the steel corrosion resistance.

The similar effect of homogenization and ordering was observed in HgCdTe/CdTe films under the influence of laser shock waves. It was found that the strongest influence of LSW is in crystals with high density of initial point defects and especially in the samples with macroscopic inhomogeneites [11].

Analysis of electrical-resistance measurement shows, that the lower concentration of defect in the material, the deeper is the minimum in the *R(T)* curve at 25-35K. For example, for the steel in the austenite state deep and narrow minimum is noticed, and for the rolled steel minimum is wide and not deep. It follows, that the $R(T)$ curve parameters in the area of its minimum and the relative of electrical-resistance R_{293}/R_{5K} are sensitive to the phase state, defective structure, presence of impurities. Minimum of electrical-resistance is connected with the existance of two scattering processes of the conduction electrons: general scattering processes – on the phonons, and the scattering processes with the back turn-over of spin on the localized magnetic moments [12].

In Fig. 4 it is seen that the conduction electrons scattering on the defects in the austenite state steel is much smaller than that in the martensite state. Contribution in the electrical-conductivity caused by the scattering of the electrons on such imperfect crystal lattice as dislocations, grain borders, interphase borders, are known not to be dependent on the temperature. When the temperature decreases, contribution into resistance, caused by the scattering of the electrons in phonons, decreases. The second, Kondo contribution, caused by the scattering in the localized magnetic moments (magnetic clasters), increases logarithmatically. Superposition of these two contributions leads to the appearance of the minimum in $R(T)$ curve. It means, that homogenized steel with minimum impurities in the scattering of the conduction electrons and the greatest contribution in the scattering on the localized magnetic moments (annealed at 1273K) possesses the greatest corrosion resistance. After processing of this steel by the laser shock waves its corrosion damage practically is not found in the sufficiently aggressive metallic medium of the liquid lithium at high temperature (873K) during 100 hours.

5. CONCLUSIONS

1. Passage of the laser shock wave in the stainless steel X18H10T causes the reverse martensite $\alpha \rightarrow \gamma$ transformation due to the quasi-hydrostatic compression and increases the density of the material.
2. Reverse ($\alpha \rightarrow \gamma$) martensite transformation of steel X18H10T is caused by the rival action of the great compression strains (2 GPa) in the front of the laser shock wave and the low degree (ε~0,001) of the plastic deformation.
3. Homogenization of the austenite structure under the action of the laser shock waves and the formation of the localized magnetic moments (magnetic clasters) causes the increase of the corrosion resistance of steel X18H10T in the aggressive medium of the liquid lithium.

REFERENCES

[1] B.P.Kovalyuk, S.P.Likhtorovich, Yu.N.Nikiforov and M.M.Nischenko // *Metallofizika* **14** (1992) 43, in Russian.

[2] *Shock Waves and High-Strain-Rate Phenomena in Metals Concepts and applications*, ed.

by Marc A. Meyers and. E. Murr (Lawrence Plenum Press, New York, 1981).

[3] P.Peyre, Ch.Carboni, A.Sollier, L.Berthe, C.Richard, E. de Rios and R.Fabbro, *New trends in lasershock waves*, Vol.4760 (proceedings of SPIE, 2002), p. 654.

[4] Charles S.Montross, Tao Wei, Lin Ye, Graham Clark and Yiu-Wing Mai // *International Journal of Fatigue* (2002) 1021.

[5] B.S.Yilbas, A.F.M. Arif, S.X.Shuja, M.A.Gondal and J.Shirokof // *J.Mater. Engineering and Performance* **13** (2004) 47.

[6] A.F.M. Arif // *J.Mater. Processing Technol.* **136** (2003) 120.

[7] T. de Resseguier, P.Berterretche, M.Hallouin and J.P.Petitet // *J.Phys. IV France* **110** (2003) 821.

[8] M.L.Capp and J.M.Rigshbee // *Mater. Sci. Eng.* **62** (1985) 49.

[9] M.A.Meyers // Scripta Met. **12** (1978) 21.

[10] V.A.Yanushkevich // *Fizika i khimija obrabotky materialov* **2** (1979) 47, in Russian.

[11] V.Yakovyna, N.Berchenko, Y.Nikiforov and A.Izhnin // *Phys. Stat. Sol. (C)* **1** (2004) 682.

[12] J.Kondo // *Prog. Teor. Phys.* **32** (1964) 37.