doi.org/10.15407/tpwj2017.07.04

INVESTIGATION OF MICROPLASTIC DEFORMATION OF METAL DEPOSITED BY ELECTRIC RESISTANCE METHOD

E.V. BEREZHNAYA[1], **V.D. KUZNETSOV**[1], **V.D. KASSOV**[2] and **P.A. GAVRISH**[2]
[1]NTTU Igor Sikorsky Kyiv Polytechnic Institute
37 Pobedy Ave., 03056, Kiev, Ukaine. E-mail: elena.kassova07@gmail.com
[2]Donbass State Machine-Building Academy
72 Akademicheskaya Str., 84313, Donetsk region, Kramatorsk, Ukraine

The search for optimization of structure and properties of the deposited metal of parts is an urgent task, the solution of which allows increasing their service properties and extending the service life. The data of investigations in this direction using the electric resistance surfacing are very limited. It was found in the work that the tendency of the deposited surface layer of a part (deposited metal and HAZ) to microplastic deformation is an important factor in determination of metal sensitivity to stress concentration. A structure of the deposited metal was obtained, which is characterized by a low sensitivity to stress concentration. It was shown that increase in the content of cementite in the structure of deposited layer leads to growth in tendency of accumulating dislocations during microdeformations, and the presence of a large volume of free ferrite allows decreasing the intensity of accumulating dislocations, reducing sensitivity of the deposited metal to stress concentration. 11 Ref., 2 Tables, 5 Figures.

Keywords: *electric resistance surfacing, surface layer structure, microdeformation, stress concentration*

The process of electric resistance surfacing applying compact materials (wires, strips) is realized by joint deformation of the material welded-on and the surface layer of a part heated in the deformation zone by short current pulses [1–3]. The overlapping of welding spots between each other is achieved by rotating a part at the speed proportional to the frequency of current pulses [4]. Therefore, the electric resistance surfacing should be understood as a totality of operations of heating, deformation and cooling by water (if necessary), as a result of which the deposited layer is characterized by heterogeneity of structure and mechanical properties, as well as different sensitivity to stress concentration [5].

The presence of heterogeneous structure in the deposited layer, which is predetermined by the specifics of the surfacing process, leads to decrease in the service life of parts operating under the cyclic loads [6]. Taking into account that the tendency of the deposited layer metal to microplastic deformation is an important factor of sensitivity to stress concentration [7], the determination of the optimal structure from the point of view of physical state of the surface layers (deposited layer and HAZ) will allow a correct selection of technology for restoration of worn-out parts. The regulation of the complex of values of physical and mechanical character (mechanical properties of the surface layers metal, microstructure, residual stresses with the creation of their favorable distribution in the surface layer) is a significant reserve for providing reliability of the restored parts.

The aim of the work is the carrying out of investigations, directed to revealing the microstructure, characterized by a low resistance of microplastic deformation and a low sensitivity to stress concentration applied to the selected group of restoring and surfacing materials.

The investigation of the microplasticity of the deposited metal was carried out on the specimens under tensile deformation. The object of the investigation was the specimens of steels of 25, 40 and 40X grades, on which the electric resistance surfacing was performed applying the strip of 0.5 mm thick at the following conditions: I_s = 6.0–6.5 kA, P = 1.25–1.5 kN, t_p = 0.04–0.06 s. The material of strips was selected being identical to the steel grades of the specimens: 25 (GOST 3560–73), 40 (GOST 3560–73), 40X (GOST 21996–76). The deposited specimens were subjected to heat treatment at different conditions to change the structure of the surface layer (Table 1), as a result of which the five groups of deposited specimens were produced to investigate the microplasticity and its homogeneity deep into the deposited metal and HAZ.

To investigate the influence of structure on microplasticity of the surface layers along the longitudinal axis of the specimen, a number of reference points were made by pyramid under the load of 20 g using the microdurometer PMT-3 [6]. The prints were applied every 0.04–0.05 mm, i.e. through the distances, commensurate with the grain size of the deposited metal of the specimens investigated. The distance between the prints served as the basis for calculating the

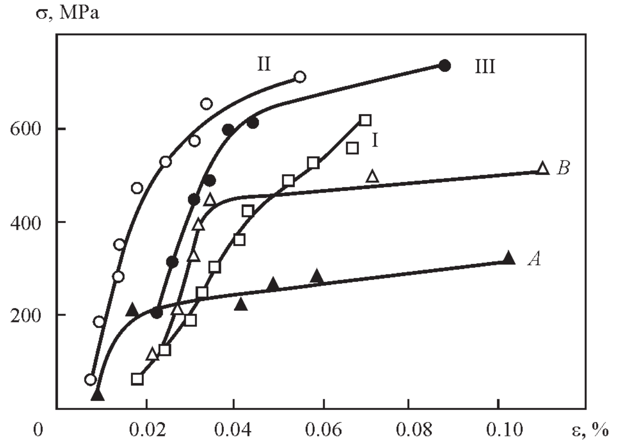

Figure 1. Experimental data on the changes in the value of microplastic deformation ε in the deposited specimens after heat treatment (see Table 1) at the increase of tensile stress σ

relative deformations under the action of the applied loads.

The analysis of the microstructure was carried out using the metallographic microscope MIM 8 with a digital photographic attachment, which provided determination of minimum loads and, correspondingly, the stresses causing a visible plastic deformation. After each next loading, the measurements of 150–160 basic distances were carried out (distances between the prints of the reference points). According to the data of measurements of the distances between the prints, the change in this distance was determined at stress increase as a result of the applied current load.

The experimental results of the investigation of the microplastic deformation of deposited specimens in a different structural state are shown in Figure 1.

The large microplastic deformation of group A deposited specimens as compared to the deposited specimens, which passed heat treatment according to the modes II, III and normalization (Figure 1), indicates a structural condition which causes an increase in fracture toughness. The low stress values indicate a higher motion of dislocations. In spite of the fact that during investigation of microplastic deformation the residual microdeformations occurred already at the lowest

Table 1. Modes of heat treatment of deposited specimens for investigation of microplasticity (holding time 1 h)

Grade of substrate steel	Group	Initial heat treatment mode		Tempering mode*	
		T, °C	Cooling medium	*T*, °C	Holding time, h
25	A	880–900	Air	620	2.5
40	B	860–880	In furnace	620	1.5
40X	I	850–870	Same	640–660	1.5
40X	II	850–870	Oil	640–660	1.5
40X	III	850–870	Same	540–560	1.5

*Furnace cooling.

stresses, under the microscope the sliding lines were detected at sufficiently high stresses (Figure 2).

It is characteristic that this stress grows with increase in the volume content of pearlite and together with decrease in the tempering temperature during heat treatment according to the mode III. In deposited specimens of the group A, the forming sliding lines are parallel. With appearance of a large amount of pearlite, the shape of sliding lines also changes, they aquire a curved nature. This phenomenon is the more distinct, the higher the volume content of perlite.

The sliding lines in sorbite-like structures (deposited specimens of the group II) are curved, they appear gradually in a wide range of stresses. At high stresses, the number of volumes with a high density of lines also increases. Thus, the shape of sliding lines depends on the obstacles for free propagation of plastic shears (near-boundary volumes, intergranular structural violations). If a deposited specimen contains a relatively large volume of grains of excessive ferrite, then there are fewer obstacles for shears, and the sliding lines are rectilinear. In sorbite structures with a developed intergranular surface, there are far more obstacles for sliding, which namely predetermines the curvature of lines.

The plastic deformation is associated with the motion of dislocations. The experimentally established values of stresses, causing the first acts of microplastic

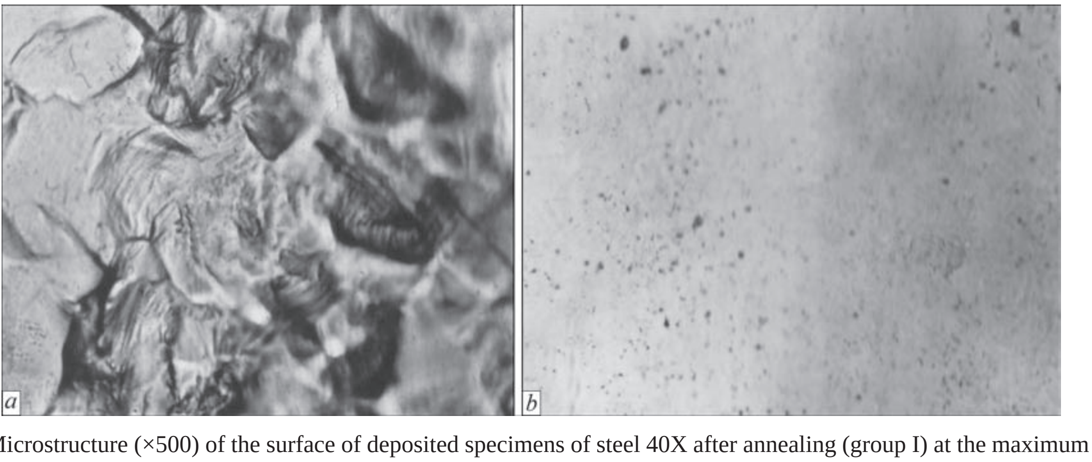

Figure 2. Microstructure (×500) of the surface of deposited specimens of steel 40X after annealing (group I) at the maximum stress of 602 MPa (*a*) and after heat treatment according to the mode II (group II) at the minimum stress of 59.804 MPa (*b*)

deformation, determine the average necessary value of stresses for the start of dislocations, causing microplastic deformation. In the deposited specimens with a low sensitivity to stress concentration, the required average value of stresses for the start of dislocations turns to be small. Consequently, the lower is the value of stresses, necessary for start of dislocation motion, the less sensitive is the specimen to stress concentration. The highest tendency to microplastic deformation is peculiar to deposited specimens of the group A, the basic structural component of which is ferrite. This is predetermined by the highest tendency to motion of dislocations under the influence of applied stresses. In the specimens mentioned above, the deformation occurs most easily, the relatively low stresses are required both for start as well as for motion of dislocations in the microvolumes. With increase in content of cementite component (pearlite), the resistance of specimens to microplastic deformation grows.

For specimens deposited of steel 25, for appearance of microplastic deformation the least stresses are required — 30.5 MPa (see Figure 1). In deposited specimens with a high content of cementite in the structure, these stresses are higher. Especially they are high for specimens, which were subjected to heat treatment after surfacing with obtaining of sorbite and troostite of tempering. For example, for deposited specimens of steel 40X with tempering sorbite (group II), the minimum stresses for appearance of microplastic deformation are 59.804 MPa (see Figure 2, *b*), and for the same specimens with tempering troostite (group III) they are 201.16 MPa (see Figure 1).

The morphology of the deposited layer surface, depending on the applied load, is conveniently observed using the method of layer-by-layer microscopy, which allows obtaining the topographic relieves of volumetric objects. The 3D-surface profile (Figure 3) shows that already at the minimum stresses, a significant uneven distribution of microdeformations over

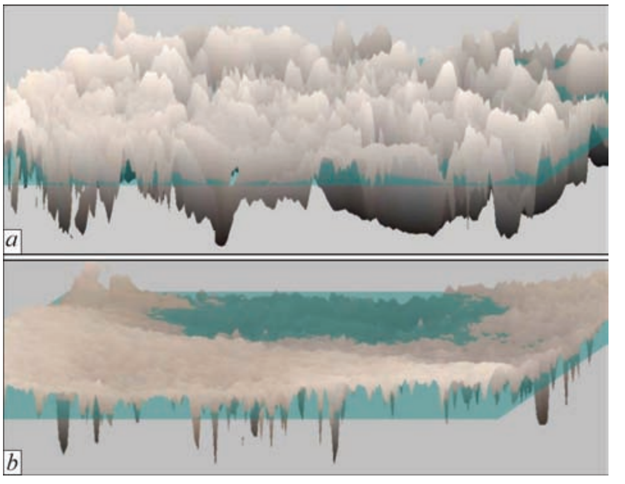

Figure 3. 3D-profiles of the deposited specimens surface of steel 40X after annealing (group I) at the maximum stress of 602 MPa (*a*) and after heat treatment according to the mode II (group II) at the minimum stress of 59.804 MPa (*b*)

the surface of the investigated deposited specimen, subjected to heat treatment, is noticeable, which indicates an increased tendency to stress concentration.

The difficulty in the motion of dislocations in the surface layer of the deposited metal leads to formation of single peaks of different value, chaotically distributed along the surface, i.e. to the formation of stress concentrators throughout the entire surface (Figure 3). At the maximum stresses, the morphology of the surface indicates an increase in the dimensions of the surface irregularities with a significant increase in separate peaks and the frequency of irregularities (see Figure 3, *a*). The growth of height of irregularities can be the result of a high resistance to dislocations motion.

There is a relation between the behavior of dislocations (their motion, accumulation of obstacles) and the modulus of plasticity. In particular, the higher the modulus of plasticity, the faster is accumulation of dislocations and the higher is the sensitivity of material to stress concentration [8, 9]. The modulus of plasticity (hardening coefficient) was determined using

Table 2. Equations, approximating the dependence of experimental data of the hardening coefficient on the degree of relative deformation

Metal of surfacing on steels	Heat treatment	Group	Structure	Form of equation
25	Normalization	A	Ferrite + pearlite	$D = 4.6226 - 27.1629\varepsilon_i + \frac{0.0068}{\varepsilon_i}$
40	Same	B	Pearlite + ferrite	$D = 4.7773 - 42.8378\varepsilon_i + \frac{0.0121}{\varepsilon_i}$
40X	Annealing	I	Same	$D = 6.643 - 45.5734\varepsilon_i + \frac{0.0068}{\varepsilon_i}$
40X	Heat treatment by the mode II	II	Sorbite	$D = 6,7291 - 48,2929\varepsilon_i + \frac{0,0023}{\varepsilon_i}$
40X	Heat treatment by the mode III	III	Troostite	$D = 5.2241 - 6.10107\varepsilon_i + \frac{0.0074}{\varepsilon_i}$

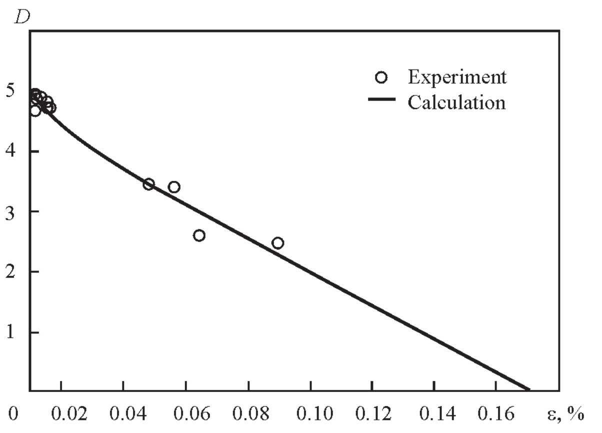

Figure 4. Changes in the coefficient of hardening *D*, depending on average total microplastic deformation ε of the deposited specimens of steel 25 in the normalized state (group A)

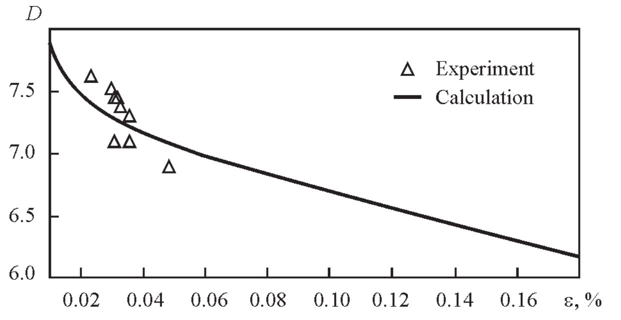

Figure 5. Changes in the coefficient of hardening *D*, depending on the average total microplastic deformation ε of deposited specimens of steel 40X after heat treatment according to the mode III (group III)

the modeling methods in the software environment of StatSoftStatisticaV6.0 (Table 2, Figure 4, 5).

Therefore, the values of hardening coefficient at microplastic deformation are not the same for different structural states and the degree of deformation, which correlates with the data of the works [10, 11]. Among the investigated specimens, the specimens of the group A are characterized by the lowest hardening coefficient (see Figure 4), and the highest hardening coefficient is peculiar to the specimens deposited in the state after heat treatment according to the mode III (see Figure 5). With increase in the degree of deformation, the hardening coefficient decreases in all the investigated structural states, which indicates the dependence of plastic flow process on the degree of microdeformation.

The carried out investigations of tendency of deposited metal in different structural states to microplastic deformation allowed revealing the structure of the deposited metal, which is the least sensitive to stress concentration. Thus, with the increase in the structure of cementite component, the sensitivity of the metal to stress concentration increases, and the presence of deposited layer of free ferrite in the structure reduces the intensity of accumulation of dislocations during microdeformations and, as a consequence, the sensitivity of deposited metal to stress concentration decreases. The results of investigations in this work were used during selection of the rational technology for restoration of parts.

Conclusions

1. The effect of the structure on the microplasticity of specimens, deposited by electric resistance surfacing, was investigated. It was shown that the deposited metal, in which in the process of microdeformation the conditions preventing the motion of dislocations are not so intensively accumulated, is less prone to stress concentration.

2. The effect of hardening coefficient on sensitivity to stress concentration as-applied to specimens deposited by strips of structural carbon steels with the subsequent heat treatment was experimentally confirmed. It was established that the highest resistance to microplastic deformation is observed in the deposited specimens after their heat treatment with obtaining of sorbite and troostite, which is associated with a more developed uneven distribution of microdeformations over the specimen surface and increase in the number of obstacles for motion of dislocations.

1. Burak, P.I. (2007) Driving forces of cohesion and formation of surface bonding process in electric resistance welding-on. *Int. Techn. and Economic J.*, 4(**4**), 33–37.
2. Sajfullin, R.N. (2008) Restoration of machine parts by electric resistance welding-on of metal-powder compositions. *Tekhnika v Selskom Khozyajstve*, **2**, 26–28.
3. Sajfullin, R.N. (2009) Restoration of parts by electric resistance welding-on with flux-cored wire. *Mekhanizatsiya i Elektrifikatsiya Selskogo Khozyajstva*, **1**, 27–28.
4. Pontileenko, F.I., Lyalyakin, V.P., Ivanov, V.P. et al. (2003) *Restoration of machine parts*: Refer. Book. Moscow: Mashinostroenie.
5. Chernoivanov, V.I., Lyalyakin, V.P. (2003) *Organizing and technology of restoration of parts*. Moscow: GOSNITI.
6. Golovin, S.A., Pushkar, A. (1980) Microplasticity and fatigue of metals. Moscow: Metallurgiya.
7. Madyanov, S.A., Kalinin, V.R., Kraev, A.P. et al. (1990) Examination of microplastic deformation as a method of evaluation of metal embrittlement. In: *Mechanics and physics of fracture of brittle materials: Transact*. Kiev, 33–38.
8. Isaev, N.V. Shumilin, S.E., Zabrodin, P.A. et al. (2013) Strain hardening and stepwise deformation of ultrafine-grained polycrystals of solid solution Al–Li at temperature of 0.5 K. *Fizika Nizkikh Temperatur*, 39(**7**), 818–826.
9. Markashova, L.I., Alekseenko, T.A., Zhdanov, S.L. et al. (2013) Influence of external static loading on change of metal structure parameters of over-heat area in HAZ of high-strength steel welded joints. *Visnyk Chernigiv. Derzh. Tekhnol. Un-tu*, 63(**1**), 87–92.
10. Terentiev, V.F. (2006) Fatigue of high-strength steels. Part 1: Correlation with ultimate strength, types of curves and crack initiation. *Deformatsiya i Razrusheniya Materialov*, **8**, 2–11.
11. Chapetti, M.D., Tagawa, T., Miyata T. (2003) Ultra-long cycle fatigue of high-strength carbon steels. Part 1: Revive and analysis of the mechanism of failure. *Mater. Sci. & Engin. A*, 356(**1/2**), 227–235.

Received 13.09.2017