EFFECT OF STRUCTURAL-PHASE TRANSFORMATIONS IN ALUMINIUM-LITHIUM ALLOY 1460 JOINTS ON PHYSICAL-MECHANICAL PROPERTIES

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Analysis of experimental data on evaluation of mechanical properties of the alloy joints was performed by taking into account the weld metal composition, grain and sub-grain sizes, real dislocation density, volume content of phase precipitates, etc. The effect of each of the specific structural-phase parameters on mechanical characteristics of the welded joints and their change under the influence of postweld heat treatments and external loading was determined.

Keywords: *heat treatment, weld metal, aluminium alloy, scandium, fine structure, phase precipitates, dislocation density, composite phase precipitates*

At present there is a growth of commercial demand for materials with special properties. Especially this applies to super-light materials used in aircraft and aerospace engineering, where it is necessary to ensure the sufficient level of specific strength, ductility and crack resistance under complex service conditions [1, 2]. Such materials include, in particular, aluminium-lithium alloys, which are characterised by a high technological effectiveness and the required level of properties at cryogenic and increased temperatures.

However, some important properties of Al–Li alloys dramatically change during fabrication and operation of structures, which is related primarily to special structural-phase transformations occurring in these materials in the course of different technological operations [2, 3], including under the effect of the welding process. As to Al–Li alloys with scandium additions, in this case their phase composition may become even more complicated, since alloys of this type belong to materials that are susceptible to ageing and feature, as a rule, a special complexity of phase transformations occurring under a thermal effect, including heat treatment [4, 5]. It is significant from this standpoint that mechanical properties of alloys of this type also change under the effect of heat treatment, this being related to the impact of structural factors [2, 4–8] (Table).

Therefore, allowing for a complex structural state of this type of materials, and particularly for the phase formation processes under various thermal-deformation impacts, it is important to evaluate the effect of specific structural-phase components on changes in mechanical characteristics of the welded joints that are most significant for service conditions, i.e. strength and toughness values.

It is of interest to investigate the effect of structure of metal of the welded joints on the character of its deformation under external loading, i.e. the effect of structural and phase components on the processes of accumulation of internal stresses and the probability of their plastic relaxation, which is an indicator of crack resistance of the deformed material.

To address the tasks posed, first of all it is necessary to have the comprehensive experimental data base, giving a real view of the structural-phase state of an investigated material, which is formed by using the technological welding parameters, as well as of the changes in this state under conditions of postweld heat treatments and external loading.

The basic experimental information on the structural-phase state of the weld metal of the joints on aluminium alloy 1460 (Al–3 % Cu–2 % Li–0.08 % Sc) welded by using filler wire Sv1201 (Al–6.5 % Cu–0.25 % Zr–0.3 % Mn) with 0.5 % Sc and without it, which is required for analytical evaluation of mechanical properties of the materials studied, was generated from the investigations conducted at the following

Mechanical properties of metal of the joint on alloy 1460 welded by using filler wires Sv1201 and Sv1201 + Sc in the as-welded state and after heat treatment

Type of treatment	Sv1201			Sv1201 + Sc		
	σ_t, MPa	$\sigma_{0.2}$, MPa	*HRB*	σ_t, MPa	$\sigma_{0.2}$, MPa	*HRB*
As-welded	250.0	175.0	75.0	282.2	189.6	81
After artificial ageing (T = 150 °C, t = 22 h)	316.0	281.5	78.0	337.0	240.3	85
After annealing (T = 350 °C, t = 1 h)	248.2	204.3	71.7	345.5	295.0	92

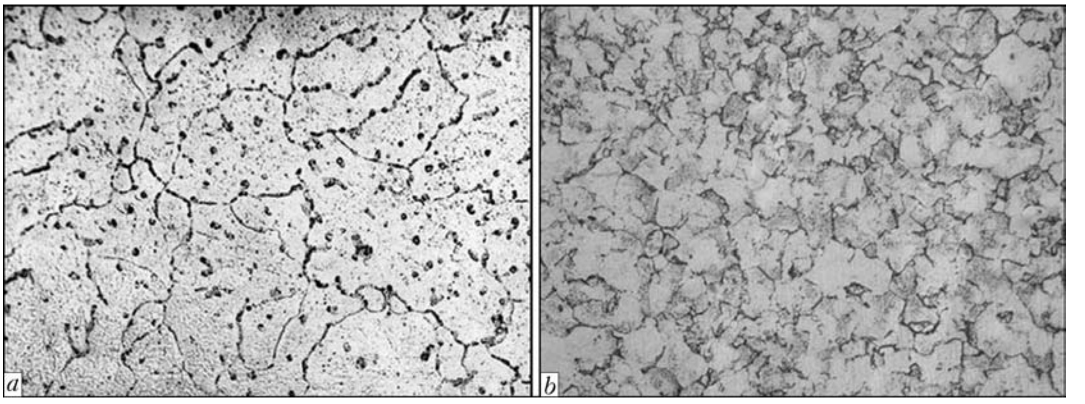

Figure 1. Microstructure (×500) of weld metal of the joint on alloy 1460 welded by using filler wires Sv1201 (*a*) and Sv1201 + 0.5 % Sc (*b*)

stages: immediately after argon-arc welding (*I*), after postweld heat treatments (*II*) (artificial ageing at T = = 150 °C, t = 22 h, and annealing at T = 350 °C, t = = 1 h), and after external dynamic loading (*III*). The comprehensive investigations, including chemical analysis of metal of the welded joint, character of the grain, sub-grain and dislocation structure, as well as phase precipitates of complex composition, morphology and distribution at different stages of their formation, were carried out by using optical, analytical scanning microscopy (SEM-515, «Philips», the Netherlands), as well as microdiffraction transmission electron microscopy (JEM-200CX, JEOL, Japan) with an accelerating voltage of 200 kV. Thin foils for transmission microscopy were prepared by the method of ion thinning with ionised argon flows in a specially developed unit [9].

The following was established as a result of preliminary investigations [10–12]. No special differences in distribution of chemical elements in the weld metal were detected during the solidification process (as-welded state) at the absence of scandium in filler wire (*I*) and with scandium added to filler wire (*II*). A complex saturated solid solution of main alloying elements of copper and lithium was formed in both cases, the weight content of copper being minimal at the centre of grains and increasing to some extent towards the grain boundaries. However, the characteristic feature of alloying with scandium was formation of isolated scandium segregations (0.06–0.80 %).

Changes in grain structure were more substantial — alloying with scandium led to a considerable (two-times) refinement of the grain structure (Figure 1). More substantial differences were noted also in the character of fine structure. Whereas the weld metal without addition of scandium (*I*) was characterised by a comparatively uniform distribution of dislocations (Figure 2, *a*) at their low density (approximately $(2–5)\cdot10^9$ cm^{-2}), in the case of scandium additions (*II*) the density of dislocations grew by an order of magnitude (from $6\cdot10^9$ to $(5–6)\cdot10^{10}$ cm^{-2}) and their distribution was irregular (Figure 3, *a*, *b*), the tendency being to formation of intragranular, slightly disoriented sub-structures.

As to the phase formation processes, formation of phases of rather big sizes (more than 1–2 μm) (complex conglomerates of the Al–Cu and Al–Li phases), as well as phases of more dispersed sizes (Zr- and Li-containing phases) was fixed in both cases in the bulk of grains in the as-welded state.

However, the most characteristic peculiarity (refers to the Sc-containing states) was formation of a special type of structures, i.e. the Guinier–Preston (GP) zones, in the Sc-containing weld metal, the said zones looking like dense dislocation loops (see Figure 3, *a*) distributed in the segregation clusters of scandium, which was most probably related to the initial stages of decomposition of solid solution.

Some differences in structure of the grain boundaries were fixed also in the as-welded state for the investigated cases of alloying of the weld metal. For instance, fairly wide (approximately 0.1–0.4 μm) interlayers consisting of dense clusters of the globular lithium phases were clearly seen along the grain boundaries at the absence of scandium additions (see Figure 2, *b*). In addition, also characteristic is appearance of extended grain-boundary eutectic formations: either complex phases of Al–Cu type, or conglomerate of phases of Al–Cu, Al–Li type, the composition of grain boundary eutectics being similar to that of coarse intragranular phase precipitates (Figure 2, *a*).

The weld metal in the case of alloying with scandium was characterised by differences both in structure of the grain boundaries proper and in phase formation in this zone. For instance, phases of a different type (Al_3Li, Al_3Sc) and of a smaller size formed in the grain boundary zones (Figure 3, *b*).

The grain boundary eutectics characterised by non-uniform sizes and morphologies were also much different. Moreover, along with dense, monolithic eutectic formations, which are more typical of a case of the absence of scandium, increase in volume of friable eutectics with inclusions of the dispersed Sc-containing phases was fixed (Figure 3, *a*).

Investigations of the state of the weld metal after heat treatment (T = 350 °C, t = 1 h) showed a more active redistribution of chemical elements and a change in structure (see Figure 1) independently of

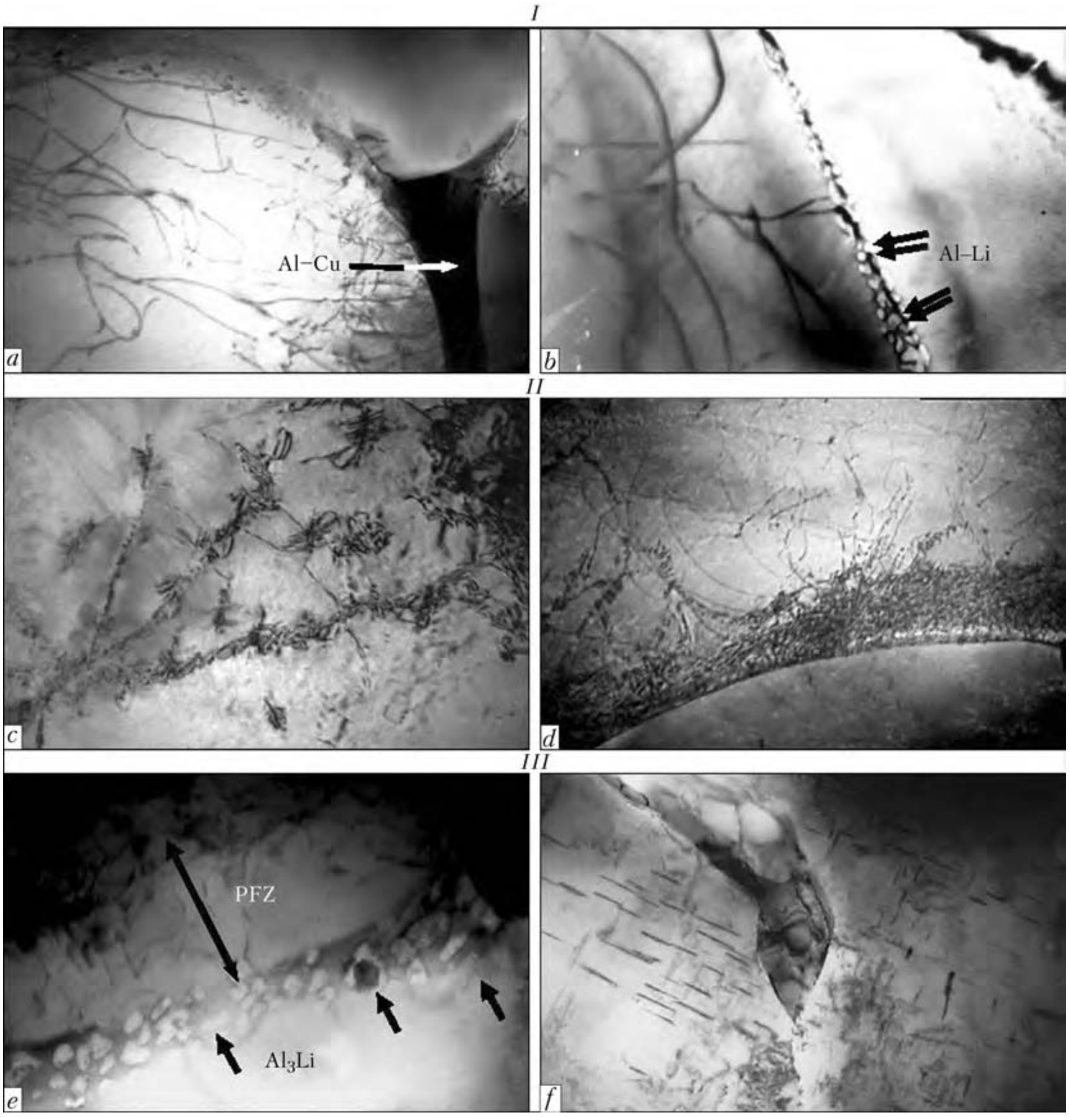

Figure 2. Fine structure of weld metal of the joint on alloy 1460 welded by using filler wire Sv1201 in the as-welded state (*I*), after heat treatments at T = 150 °C, t = 22 h (*II*) and at T = 350 °C, t = 1 h (*III*): *a* — extended grain-boundary eutectics (phases of the Al–Cu type) (×30,000); *b* — precipitation of phases of the Al–Li type along grain boundaries (×30,000); *c*, *d* — distribution of dislocations and dispersed phases, respectively, in the bulk of grains (×30,000) and along the grain boundaries (×20,000); *e* — decrease in density of distribution of phases (θ′, δ′) and dislocations in near-boundary PFZ (×50,000); *f* — eutectics at the grain boundaries (×20,000)

the type of filler wire, this most probably being caused by the processes of decomposition of solid solution and subsequent formation of new phases. In addition, in a case of the presence of scandium there was a marked increase in general density of dislocations and activation of the processes of their redistribution. The latter is likely to be caused by a considerable violation of coherency of the matrix–phase precipitations lattices related to intensification of the phase formation processes during heat treatment, alloying in this case, which leads to an even more intensive refinement of not only the grain structure but also of the sub-structure, i.e. blocks and sub-grains (Figure 3, *e*, *f*). Moreover, activation of the phase formation processes after heat treatment, when using the indicated types of the fillers, is confirmed by a considerable increase in volume content of the intragranular phase precipitates of both medium (0.2–0.5 μm) and finer (approximately 0.01–0.03 μm) sizes.

With a change in alloying, the differences could be seen also in structure of the grain boundaries after heat treatment. For example, expansion and structural complication of the grain boundary regions after heat treatment (T = 350 °C, t = 1 h) were detected in the Sc-free weld metal. Formation of the extended grain-boundary zones free from phase precipitates (PFZ), which were also characterised by a substantial decrease in the dislocation density, was fixed, in addition to the zones with dense layers of the Li-containing phases. As a result, the PFZ regions were a laminated, grain boundary interlayers directed along the boundaries, characterised by a dramatic gradient of the dislocation density and the presence of phases (see Figure 2, *a*).

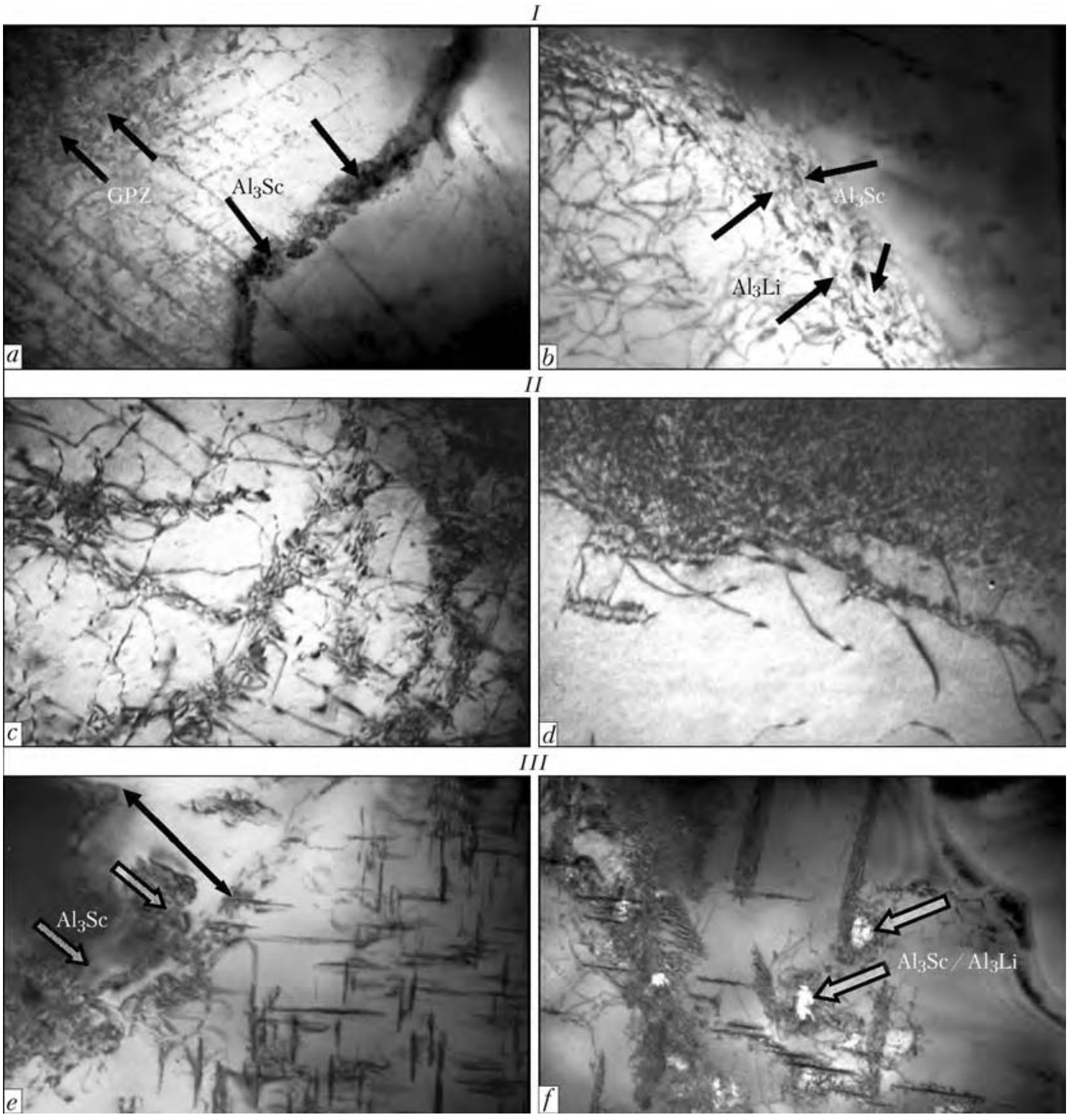

Figure 3. Fine structure of weld metal of the joint on alloy 1460 welded by using filler wire Sv1201 + Sc in the as-welded state (*I*), after heat treatments at T = 150 °C, t = 22 h (*II*) and at T = 350 °C, t = 1 h (*III*): *a* — segregation and phase precipitates in grain boundary zones of weld metal of the Al–Cu type with scandium additions (×20,000); *b* — precipitation of Al–Li phases along grain boundaries (×37,000); *c*, *d* — distribution of dislocations and ultra-dispersed phases in the bulk of grains (×30,000) and along the grain boundaries (×37,000); *e* — filling of PFZ along the grain boundary with phase precipitates Al_3Sc (×30,000); *f* — distribution of Sc- and Li-containing phases in the bulk of grains (×30,000)

In the case of an addition of scandium to the weld metal, firstly the grain boundary structure lost some of its density, i.e. the boundaries became more friable, and secondly, the volume content of the Li-containing phases along the grain boundaries substantially decreased, while the phase precipitates forming during heat treatment filled up (or made much narrower) the PFZ region adjoining the grain boundaries (Figure 3, *f*), this leading to levelling of the negative effect of this zone clearly defined at the absence of scandium.

As far as the grain boundary eutectic formations are concerned, whereas massive eutectics for the Sc-free weld metal were more stable (both in the as-welded state and after heat treatment), in the weld metal with scandium additions the eutectic during heat treatment became much more friable and decomposed into separate isolated phase formations, this leading to substantial refinement of the individual phases forming the eutectic, while a number of dispersed phase precipitates in the eutectic lost their clear outlines, this evidencing occurrence of the active processes of their diffusion dissolution.

The experimental results obtained at different structural levels, i.e. from the macro- (grain) to microlevel (dislocation), allowed analytical evaluation of the specific (differentiated) contribution made by different structural-phase parameters (phase composition, grain and sub-grain sizes, dislocation density, etc.) under corresponding thermal-deformation conditions to a change in total (integrated) values of mechanical properties, i.e. strength, ductility and crack resistance.

Evaluation of the total value of increment in yield stress $\Sigma\sigma_y$ for the weld metal of the investigated alloy (without and with scandium), allowing for chemical composition (solid solution strengthening $\Delta\sigma_{ss}$), real

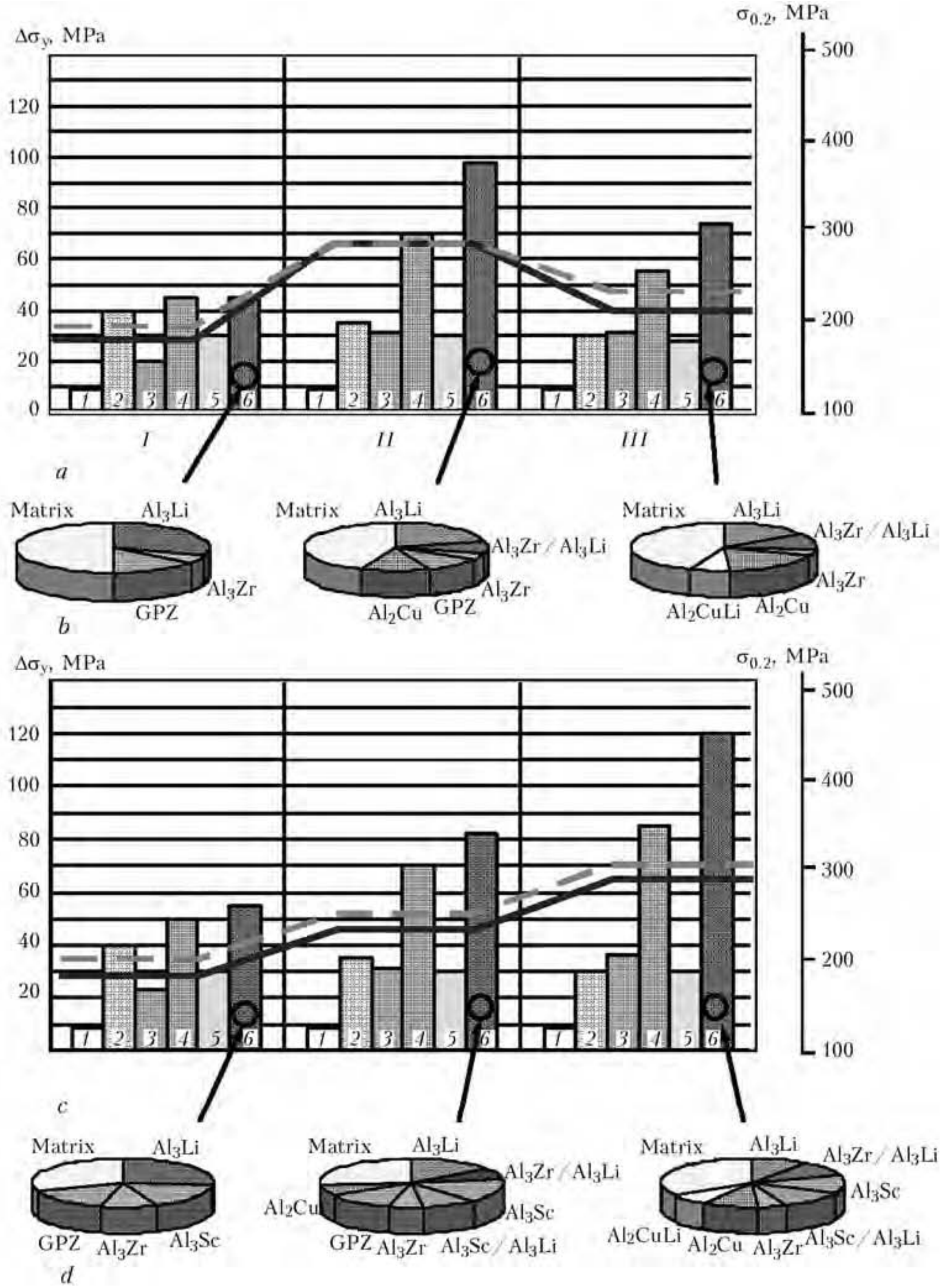

Figure 4. Histograms (*a*, *c*) of differentiated contribution of individual structural $\Delta\sigma_y$ parameters to the total (integrated) change of yield stress $\Sigma\sigma_y$ of the 1460 alloy weld metal obtained by using filler wires Sv1201 (*a*) and Sv1201 + 0.5 % Sc (*c*), and sector diagrams of volume content of the phases forming under the investigated conditions (*b*, *d*): *I* — as-welded; *II*, *III* — after heat treatments at T = 150 °C, t = 22 h, and at T = 350 °C, t = 1 h; solid line — $\sigma_{0.2}$; dashed line — σ_y; *1* — $\Delta\sigma_0$; *2* — $\Delta\sigma_{ss}$; *3* — $\Delta\sigma_g$; *4* — $\Delta\sigma_s$; *5* — $\Delta\sigma_d$; *6* — $\Delta\sigma_p$

dislocation density (dislocation strengthening $\Delta\sigma_d$), grain strengthening $\Delta\sigma_g$, sub-grain strengthening $\Delta\sigma_s$, particles of phase precipitates $\Delta\sigma_p$, etc., was made by using the Hall–Petch, Orowan and other similar relationships [13–17].

As seen from Figure 4, the total value of yield stress $\Sigma\sigma_y$ of the weld metal and the specific contribution of different $\Delta\sigma_y$ structural factors to the said characteristic vary depending on the process conditions (welding, heat treatment) and alloying. For instance, for the weld metal (compared to alloying with scandium and without it) a higher level of increment of strength characteristics σ_y was detected, i.e. approximately by 20 (10 %) and 85 MPa (26 %) higher in the as-welded state and after heat treatment (T = = 350 °C, t = 1 h).

The maximal contribution to strengthening $\Delta\sigma_y$ is made by phase formations (approximately by 40 %), and the minimal contribution — by dislocation density (by about 10 %) (see Figure 4).

Specific information on the contribution to strengthening made by other structural factors for the investigated weld metal compositions under the considered conditions is given in Figure 4.

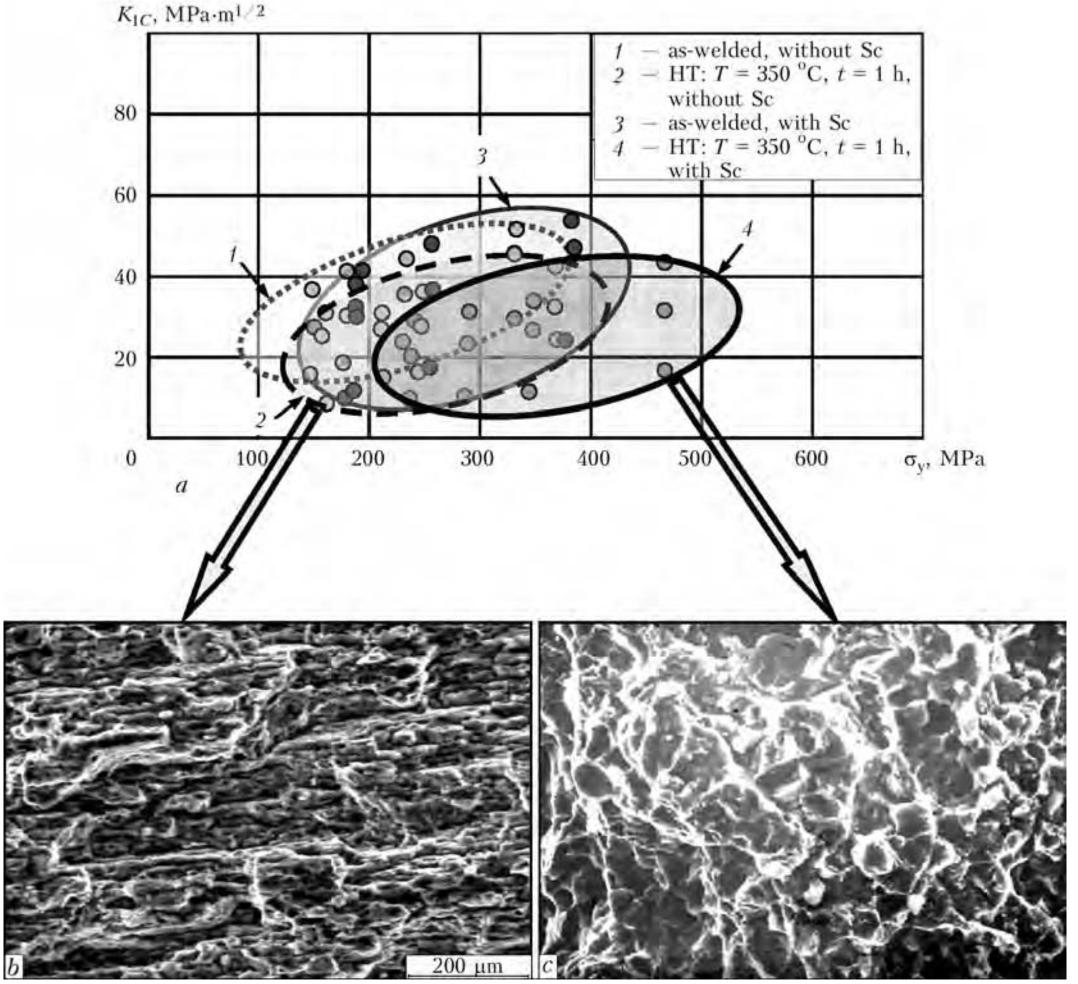

Figure 5. Diagram of changes in values of $\Sigma\sigma_y$ and fracture toughness K_{1C} of weld metal of the welded joint on alloy 1460 without scandium in the as-welded state (*1*) and after heat treatment at T = 350 °C and t = 1 h (*2*), as well as in the as-welded state with scandium (*3*) and after heat treatment of the Sc-containing weld metal performed by using the said parameters (*4*): *a* — character of fracture of the weld metal under external dynamic loading conditions; *b* — quasi-brittle fracture of metal (Sv1201); *c* — tough fracture (Sv1201 + 0.5 % Sc) with the clearly defined pit-like structure

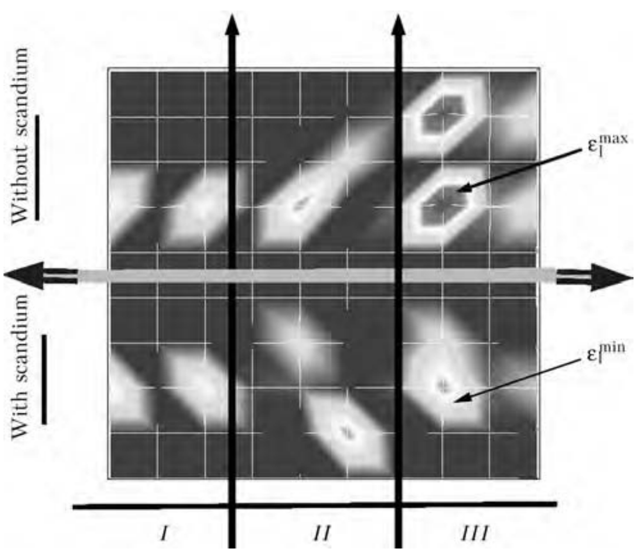

Figure 6. Diagrams of distribution of ε_l deformation localization zones in the 1460 alloy weld metal obtained by using filler wires Sv1201 and Sv1201 + Sc in the as-welded state (*I*) and after heat treatment at T = 150 °C, t = 22 h (*II*) and at T = 350 °C, t = 1 h (*III*)

The effect of structural factors on changes in parameters of fracture toughness K_{1C} of the weld metals with different types of alloying was evaluated as well (Figure 5, *a*). The K_{1C} value was determined from the Krafft relationship: $K_{1C} = (2E\sigma_y d_f)^{-1/2}$ [18], which includes experimental data of fractographic analysis of fractures, where d_f is the size of facets or pits on the fracture surface, the value of which is equated to the value of critical crack opening displacement δ_c; E is the Young modulus; and σ_y is the calculated strengthening. As shown by analysis of the results, whereas fracture toughness parameter K_{1C} of the weld metal in the as-welded state for the investigated alloying cases (without and with scandium) hardly changes with increase in the level of σ_y and equals approximately 35–36 MPa·m$^{1/2}$ (see Figure 5), in heat treatment (T = 350 °C, t = 1 h) the character of alloying does affect K_{1C}. An approximately 20 % decrease in the fracture toughness parameter was fixed at the absence of scandium, whereas in alloying with scandium, although there is an increase in strength characteristics, fracture toughness parameter K_{1C} hardly changes, this indicating to a good combination

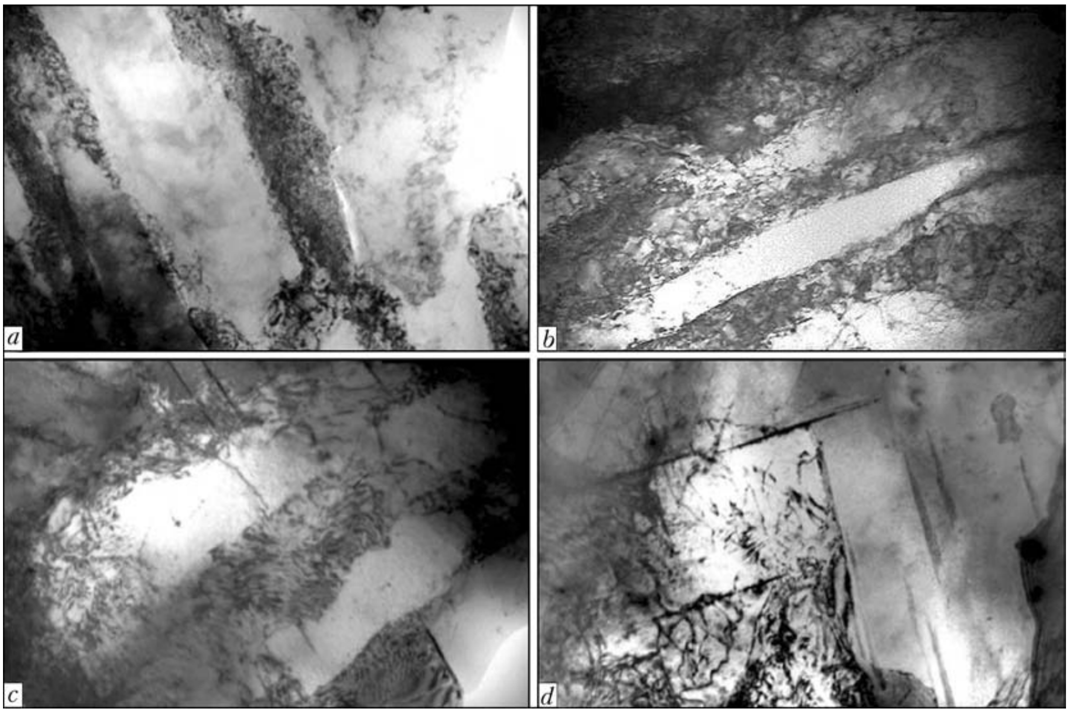

Figure 7. Changes in fine structure of heat-treated (T = 350 °C, t = 1 h) weld metal on alloy 1460 under conditions of dynamic loading depending on the alloying method (without and with scandium): *a*, *b* — intensive SBs in metal without scandium (×20,000 and ×30,000, respectively); *c*, *d* — fragmentation of structure due to blocking of SBs by the scandium phases in Sc-containing metal (×30,000)

of strength and ductile characteristics of the weld metal (see Figures 4 and 5, *a*).

As to such mechanical characteristic as crack resistance, here very significant is the character of changing of the structural state of the investigated material under external loading, especially under extreme conditions, i.e. dynamic external loadings for the welded joint with and without scandium, which was evaluated by transmission examinations of fine structure.

Examinations of the fine structure showed that, firstly, a non-uniform distribution and clearly defined localisation of deformation ε_l in microvolumes of metal take place in the Sc-free weld metal after heat treatment (T = 350 °C, t = 1 h) and subsequent dynamic loading (Figure 6). Secondly, the deformed metal acquires an unstable (meta-stable) structural state, which shows up in an avalanche-like barrier-free metal flow, this being evidenced by the presence of intensive slip systems and shear bands (SB) (Figure 7, *a*, *b*). Moreover, substantial non-uniformity in distribution of dislocation density ρ along SB is fixed in this case, where $\rho \sim 10^8$–$2\cdot10^9$ cm^{-2} (region inside SB) and $\rho \sim$ $\sim 8\cdot10^{10}$–$2\cdot10^{11}$ cm^{-2} (directly along the band bounda-

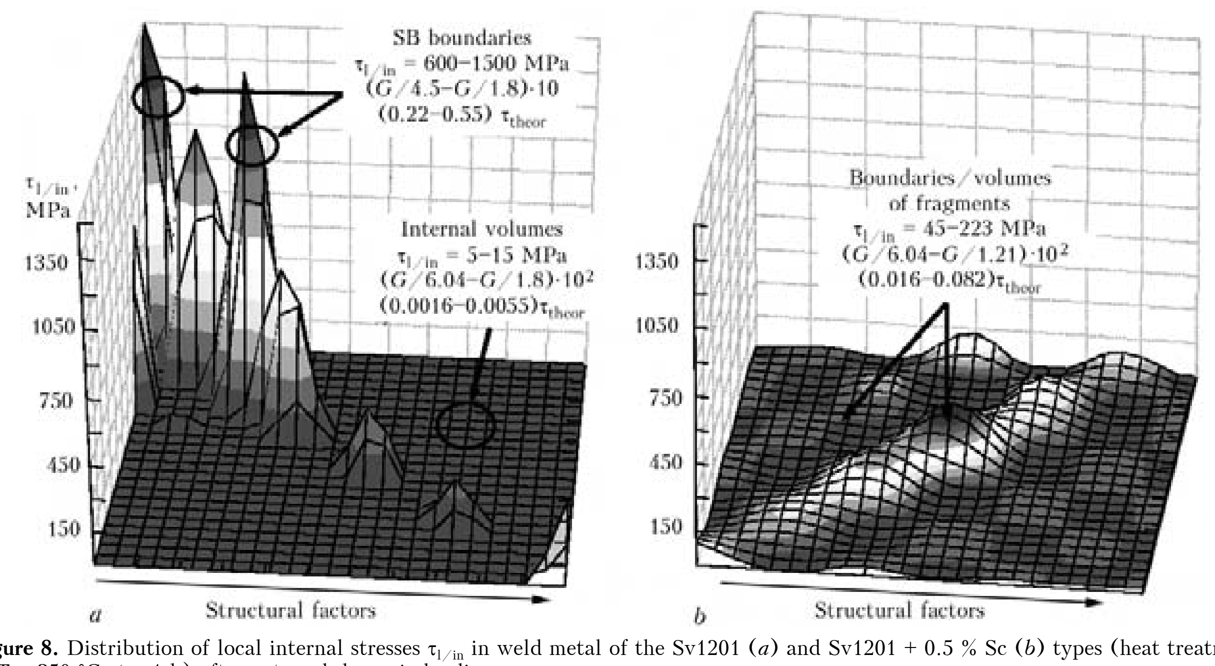

Figure 8. Distribution of local internal stresses $\tau_{l/in}$ in weld metal of the Sv1201 (*a*) and Sv1201 + 0.5 % Sc (*b*) types (heat treatment at T = 350 °C, t = 1 h) after external dynamic loading

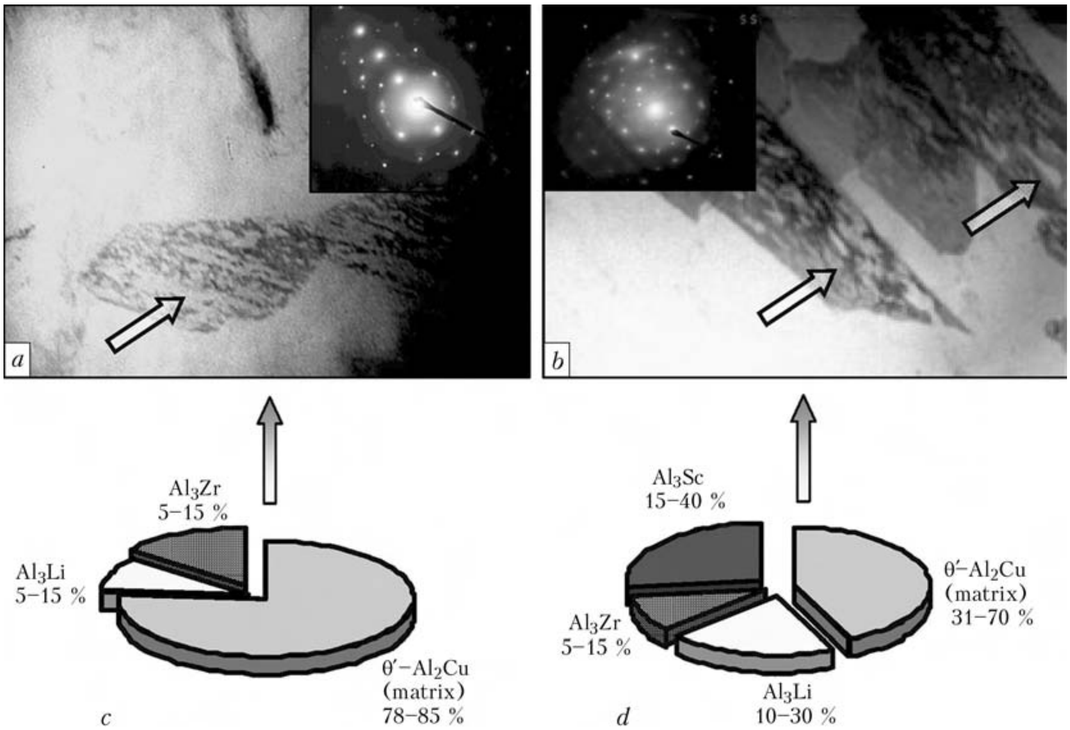

Figure 9. Changes (under heat treatment conditions at T = 350 °C, t = 1 h) in structure (a, b — ×50,000) and composition (c, d) of θ′-phase formations in weld metal of the welded joint on alloy 1460 depending on the method of alloying without (a, c) and with (b, d) scandium

ries). The latter leads to dramatic gradients in the level of local internal stresses $\Delta\tau_{l/in}$ within the zone of contact of boundaries of the band structures and their internal volumes. As shown as a result of estimation of $\tau_{l/in}$ from the Konrad and Stroh relationships, allowing for the dislocation density [19], and comparison of these values with theoretical strength τ_{theor} of the material, the band boundaries are extended local raisers of internal stresses, where $\tau_{l/in}$ is 600–1500 MPa ($G/4.5$–$G/1.8$)·10, this corresponding to (0.22–0.55)τ_{theor}. Here τ is the shear modulus. In contrast to this, in the internal volumes of SBs the values of $\tau_{l/in}$ dramatically decrease (almost by two orders of magnitude) to a level of about 5–15 MPa ((0.0016–0.0055)τ_{theor}) (Figure 8, a). Thus, dramatic extended gradient $\Delta\tau_{l/in}$ of local internal stresses forms along the shear bands, i.e. $\Delta\tau_{l/in}$ corresponds to 0.55τ_{theor} (SB boundaries)–0.0055τ_{theor} (SB volume).

Therefore, the directed local flow in the weld metal (at the absence of scandium) that leads to formation of extended raisers of internal stresses, combined with a directed dramatic gradient of such stresses along the SB boundaries, is a cause of cracking and, hence, decrease in level of not only strength and also ductility of the joints, which is proved also by a laminated character of microrelief of the surface with elements of quasi-brittle fracture of the weld metal (see Figure 5, a).

In the case of alloying with scandium a different type of structure forms in the weld metal under similar conditions of dynamic loading, this structure being characterised by a uniform distribution of dislocations and general refinement (fragmentation) of structure (see Figure 7, c, d). Stable blocking of the forming slip systems by phase precipitates of a special type, i.e. phases of the conglomerate type with Sc-containing components (see Figure 9), is fixed in this case, this leading to fragmentation (dispersion) of structure and a more uniform distribution of internal stresses ($\tau_{l/in}$ ~ 75 MPa or 0.027τ_{theor}) in the weld metal (see Figure 8, b). Formation of this type of the structures leads also to increase in the probability of plastic relaxation of internal stresses in the weld metal (especially under extreme conditions) due to involvement of additional rotation relaxation mechanisms, which is confirmed by a tough character of fracture of the joints (see Figure 5, b).

CONCLUSIONS

1. It was established that alloying the weld metal with scandium in argon-arc welding of Al–Li alloy 1460 leads to substantial dispersion of grain structure, increase in dislocation density and activation of the processes of formation of sub-structures and processes of phase formation (mostly Sc-containing phases) in the internal volumes of grains. Heat treatment (T = = 350 °C, t = 1 h) in the case of alloying with scandium promotes levelling of intergranular structures (Li-containing zones, PFZs), which are a problem for the investigated alloys.

2. Analytical evaluations of the specific (differentiated) contribution of different structural-phase parameters to changes in the properties of strength $\Delta\sigma_y$, ductility K_{1C} and crack resistance of the investigated welded joints were made. It was shown that alloying

with scandium leads to increase in the total (integrated) value of yield stress $\Sigma\sigma_y$ of the weld metal by about 20 MPa (10 %) in the as-welded state and by about 85 MPa (26 %) after heat treatment (T = 350 °C, t = 1 h). The maximal contribution to strengthening $\Sigma\sigma_y$ is made by phase formations (about 40 %), and the minimal contribution — by dislocation density (roughly up to 10 %).

3. Alloying with scandium leads to a more uniform distribution of growing local internal stresses and fragmentation of intensive SBs forming in the weld metal under dynamic loading, which is favourable for crack resistance of the welded joint and leads to increase in relaxation ability of the weld metal due to involvement of the additional (rotation) mechanisms of plastic relaxation to the dislocation ones.

1. Fridlyander, I.N., Chuistov, K.V., Berezina, A.L. et al. (1992) *Aluminium-lithium alloys. Structure and properties*. Kiev: Naukova Dumka.
2. Furukawa, M., Berbon, P., Horita, Z. et al. (1997) Production of ultrafine-grained metallic materials using an intense plastic straining technique. *Mater. Sci. Forum*, **233**/**234**, 177–184.
3. Ryazantsev, V.I., Fedoseev, V.A. (1994) Mechanical properties of welded joints on Al–Cu system aluminium alloys. *Svarochn. Proizvodstvo*, **12**, 4–7.
4. Tsenev, N.K., Valiev, R.Z., Obraztsov, O.V. et al. (1992) Mechanical properties of submicron grained Al–Li alloys. In: *Proc. of 6th Int. Aluminium Conf.* (Germany, Garmisch-Partenkirchen, Oct. 8–10, 1992), 1125–1135.
5. Ball, H.D., Lloyd, D.J. (1985) Particles apparently exhibiting fivefold symmetry in Al–Li–Cu alloys. *Scr. Met.*, **19**, 1065–1068.
6. Gayle, F.W., Vander Sande, J.B. (1984) Composite precipitates in an Al–Li–Zr alloy. *Ibid.*, **18**, 473–478.
7. Gufnghui, M., Huasyun, Y., Delin, P. et al. (2000) Fraction and phase spacing of fibrous intermetallic S-LiAl in hypoeutectic Al–Li alloys by unidirectional solidification. *Metallofizika. Nov. Tekhnologii*, 22(**4**), 58–61.
8. Furukawa, M., Miura, Y., Nemoto, M. (1987) Temperature and strain rate dependences of yield stress of an Al–Cu–Li–Mg–Zr alloy. *Transact. of JIM*, **28**, 655–665.
9. Darovsky, Yu.F., Markashova, L.I., Abramov, N.P. et al. (1985) Method of preparation for electron-microscopic analyses. *Avtomatich. Svarka*, **12**, 60.
10. Markashova, L.I., Grigorenko, G.M., Ishchenko, A.Ya. et al. (2006) Effect of scandium additions on structure-phase condition of weld metal produced by welding aluminium alloy 1460. *The Paton Welding J.*, **1**, 16–23.
11. Markashova, L.I., Grigorenko, G.M., Ishchenko, A.Ya. et al. (2006) Effect of scandium additions on the fine structure of weld metal in aluminium alloy 1460 welded joints. *Ibid.*, **2**, 20–25.
12. Markashova, L.I., Grigorenko, G.M., Lozovskaya, A.V. et al. (2006) Effect of scandium additions on structure-phase state of weld metal in aluminium alloy joints after heat treatment. *Ibid.*, **6**, 7–11.
13. Konrad, G. (1973) Model of strain hardening for explanation of grain size effect on metal flow stress. In: *Ultrafine grain in metals*. Moscow: Metallurgiya.
14. Petch, N.J. (1953) The cleavage strength of polycrystalline. *J. Iron and Steel Inst.*, 173(**1**), 25–28.
15. Orowan, E. (1954) *Dislocation in metals*. New York: AIME.
16. Ashby, M.F. (1983) Mechanisms of deformation and fracture. *Adv. Appl. Mech.*, **23**, 118–177.
17. Kelly, A., Nicholson, R. (1966) *Precipitation hardening*. Moscow: Metallurgiya.
18. Romaniv, O.N. (1979) *Fracture toughness of structural steels*. Moscow: Metallugiya.
19. Ivanova, V.S., Gordienko, L.K., Geminov, V.N. et al. (1965) *Role of dislocations in strengthening and fracture of metals*. Moscow: Nauka.