INFLUENCE OF WELDING PROCESSES ON THE STRUCTURE AND MECHANICAL PROPERTIES OF WELDED JOINTS OF ALUMINUIM ALLOY 1460

L.I. MARKASHOVA, A.G. POKLYATSKY and **O.S. KUSHNARYOVA**
E.O. Paton Electric Welding Institute, NASU
11 Bozhenko Str., 03680, Kiev, Ukraine. E-mail: office@paton.kiev.ua

An essential difference in formation of structural-phase state of weld metal of aluminium alloy 1460 at application of various technological conditions of welding is shown. In nonconsumable electrode argon-arc welding the weld metal is characterized by an essential increase of the dimensions of phase precipitates in inner grain bulk, formation of massive extended eutectics of intergranular type, as well as a pronounced coarsening of granular structure, that is related to active development of the processes of collective recrystallization under the impact of temperature mode of welding. Structural-phase state of weld metal under the conditions of friction stir welding is characterized by a more marked dispersion of phase precipitates and their uniform distribution, as well as grain refinement as a result of dynamic recrystallization, due to intensive impact of deformation processes localized in the welding zone. 11 Ref., 6 Figures.

Keywords: *aluminium alloy 1460, nonconsumable electrode argon-arc welding, friction stir welding, phase precipitates, dislocation strengthening, strength characteristics*

Engineering demand for various materials is determined, as a rule, by the possibility of providing the required set of service characteristics of metals and alloys of a certain class, as well as their welded joints. This is particularly true for superlight materials, including Al–Li alloys, used in aircraft and aerospace engineering, where it is necessary to guarantee not only a high adaptability to fabrication, but also the required level of strength, ductility and crack resistance under complex service conditions, also at cryogenic and elevated temperatures [1, 2]. Considering that practically all the properties of any materials are determined mainly by their structural-phase state that undergoes essential changes under different conditions of thermodeformational impact, it is rational to study the most significant structural components formed in the welded joint metal under the influence of the used technological conditions. It is particularly urgent for welded joints of complex-alloyed aluminium alloys, which are characterized by an abrupt change of not only the structures, but also phase precipitates (PP) during various technological operations, also under the impact of welding processes.

In addition, at selection of the most optimum processes of aluminium alloy welding it is believed to be interesting to assess the role of the main structural components (PP, dislocation density, substructures) in variation of welded joint strength and crack resistance that is exactly the objective of this work.

Material and procedures. In this work welded joints of sheet (rolled) high-strength Al–Li alloy 1460 2 mm thick were studied with application of two welding processes. The first process is automatic nonconsumable electrode argon-arc (TIG) welding at the speed of 20 m/h in MW-450 system (Fronius, Austria) at 140 A current, using Sv1201 welding wire as filler material. The second process is friction stir welding (FSW) performed in the laboratory unit designed at PWI. In the last case a special tool with a conical tip and edge of 12 mm diameter was used to produce butt joints, its rotation speed being 1420 rpm, and linear speed of its displacement along the butt was 14 m/h. Samples for research performance were prepared from the base metal and weld metal of joints.

Basic experimental information about the nature of the main structural components, having a considerable influence on service properties of welded joints, particularly, structural-phase transformations, which occur at the change of welding processes, was obtained with application of optical and transmission microdiffraction electronic microscopy (JEOL JEM-200CX) at accelerating voltage of 200 kV. Thin foils for transmission studies were made by a two-step method — preliminary electric polishing with subsequent multiple ion thinning by ionized flows of argon in a specially developed unit [3]. The latter allowed not only widening the inves-

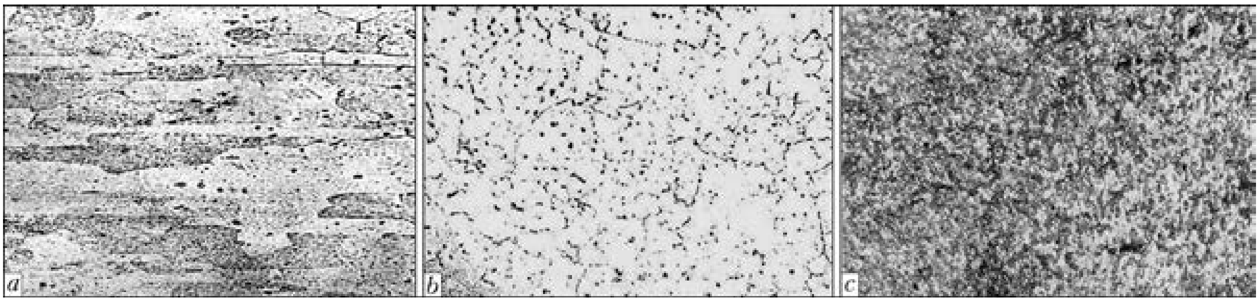

Figure 1. Microstructures (×400) of base metal of 1460 alloy (*a*) and welds made by TIG welding (*b*) and FSW (*c*)

tigation fields (increasing the statistics), but also making all the structural-phase components of analyzed material «transparent» for the electrons.

Investigation results. The structure, as well as fine structure of base metal and welds of welded joints of high-strength Al–Li alloy 1460 made by TIG welding and FSW was studied.

Base metal. As shown by optical and electron microscopy investigations, base metal of 1460 alloy is characterized by a structure with grain size d_{gr} = 10–40 μm (Figure 1, *a*), high (of the order of $1-3\cdot10^{11}$ cm^{-2}) and relatively uniform (along certain directions) dislocation density ρ (Figure 2). Here formation of a more fine-grained cellular structure (Figure 2, *a*, *c*) of dimensions d_c ~ ~ 0.15–0.40 μm and substructure of dimensions d_s in the range of 0.7–3.2 μm (Figure 2, *d*) is observed in some base metal grains. Obtained photos reveal the orientation of structural components (grains, subgrains) with different dislocation density that is characteristic for band structures forming under the conditions of oriented deformation (for instance, rolling). As regards PP, in the base metal PP of Al–Li, Al–Cu and similar types are relatively uniformly distributed both in the inner volumes and along matrix grain boundaries, but do not have any

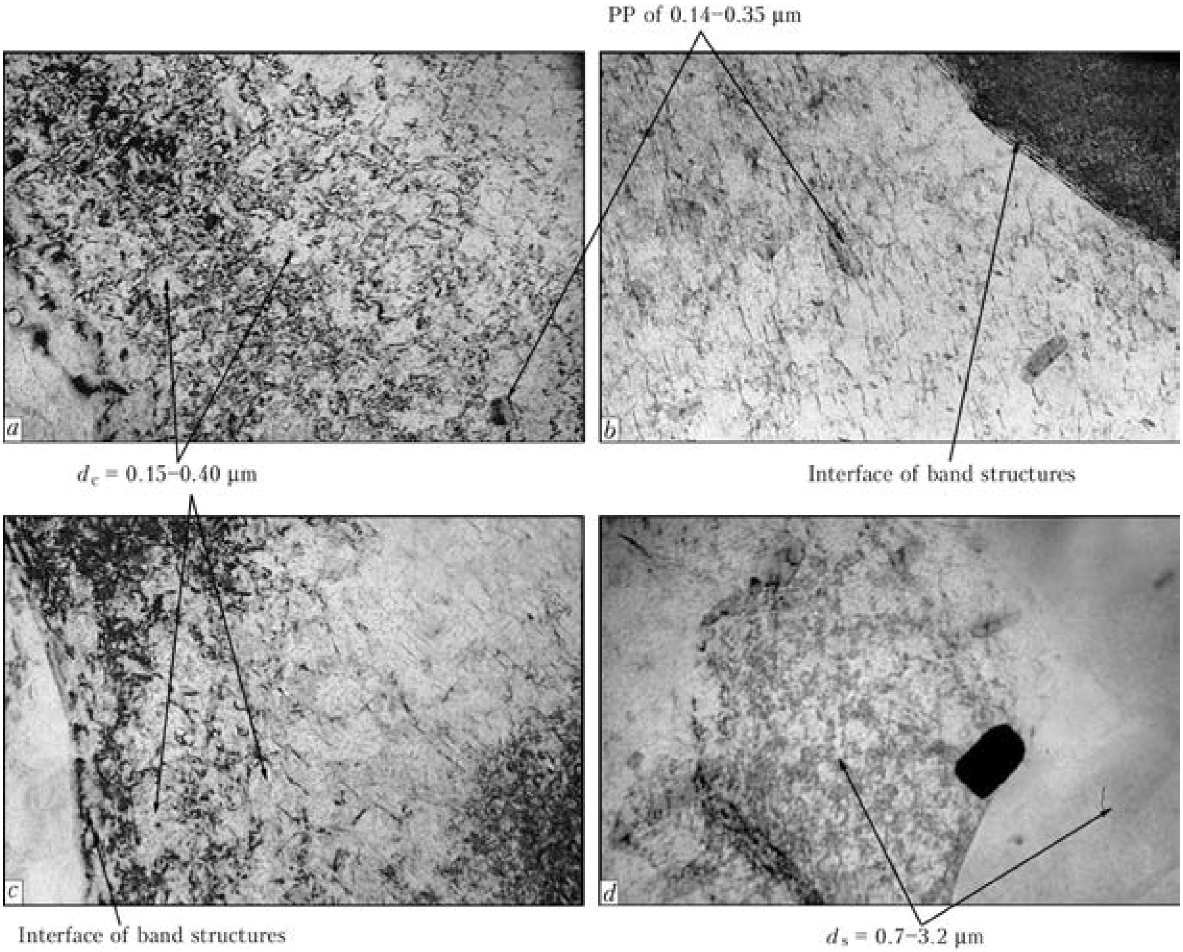

Figure 2. Microstructures of base metal of aluminium alloy 1460: *a*, *b* — distribution of dislocations and PP in inner grain volumes (*a* — ×20000, *b* — ×37000); *c*, *d* — same along grain boundaries (*c*, *d* — ×30000)

clearcut orientation. Dimensions of such PP are equal to approximately 0.14–0.35 μm (see Figure 2, *a*, *b*).

Structural-phase state of weld metal in TIG welding. The structure, as well as fine structure of weld metal of high-strength Al–Li alloy 1460 after TIG welding is characterized by lowering of dislocation density by two orders of magnitude to $\rho \sim 2–6 \cdot 10^{9}$ cm^{-2} (Figure 3), compared to the level of density in the base metal. In addition, rectilinearity of individual dislocations at their uniform distribution, absence of dislocation clusters, and overall rather considerable coarsening of the structure (by almost 2 times) (see Figure 1, *b*) is indicative not only of active development of the processes of collective solidification (through migration of primary grain boundaries), but also of equilibrium of coarse-grained structure of weld metal, forming under the conditions of fusion welding.

A feature of the structure of metal of welds made by TIG welding also is the nature of PP, their dimensions and distribution in different weld zones. A characteristic feature of phase formation under TIG welding conditions is formation of two PP types. With the first type PP are formed along grain boundaries (phases of intergranular type), and they are eutectic formations of thickness up to $\delta \sim 0.2–0.5$ μm at their considerable extent (approximately 2.0–2.5 μm) (Figure 3, *a*, *b*). The second type of PP are phases of intragranular type (Figure 3, *c*, *d*), which are characterized by a globular shape and large dimensions (approximately 6 times larger than those in the base metal). In addition, the volume fraction of such intragranular PP is much smaller compared to volume fraction of those in the base (initial) metal.

Structural-phase state of weld metal in FSW. It is found that the metal of welds of Al–Li alloy 1460 is characterized by distinct features of the main structural components, namely granular, subgranular, dislocation and phase. So, unlike the essential coarsening of the grains by the mechanism of collective recrystallization, characteristic for the conditions of fusion welding, structural transformations of another type are observed in the metal of FSW welds, namely considerable structure refinement (see Figure 1, *c*), associated with actively running processes of dynamic recrystallization, i.e. recrystallization by the nucleation mechanism. Total dislocation density increases up to $\rho \sim 3–6 \cdot 10^{10}$ cm^{-2} that is by an order of magnitude higher than bulk dis-

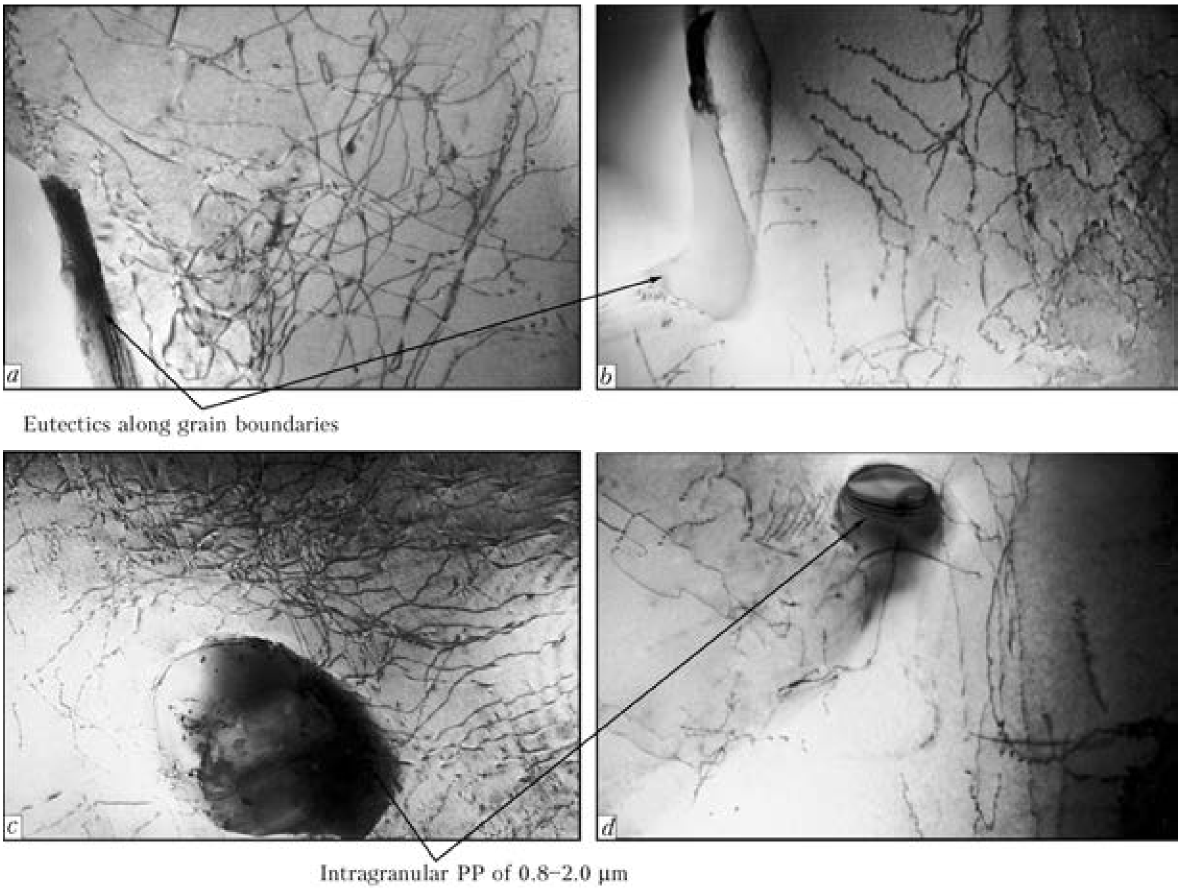

Figure 3. Microstructures of weld metal of alloy 1460 made by TIG welding: *a*, *b* — extended grain boundary eutectics (*a* — ×30000; *b* — ×20000); *c*, *d* — PP in inner grain volumes (*c* — ×20000, *d* — ×30000)

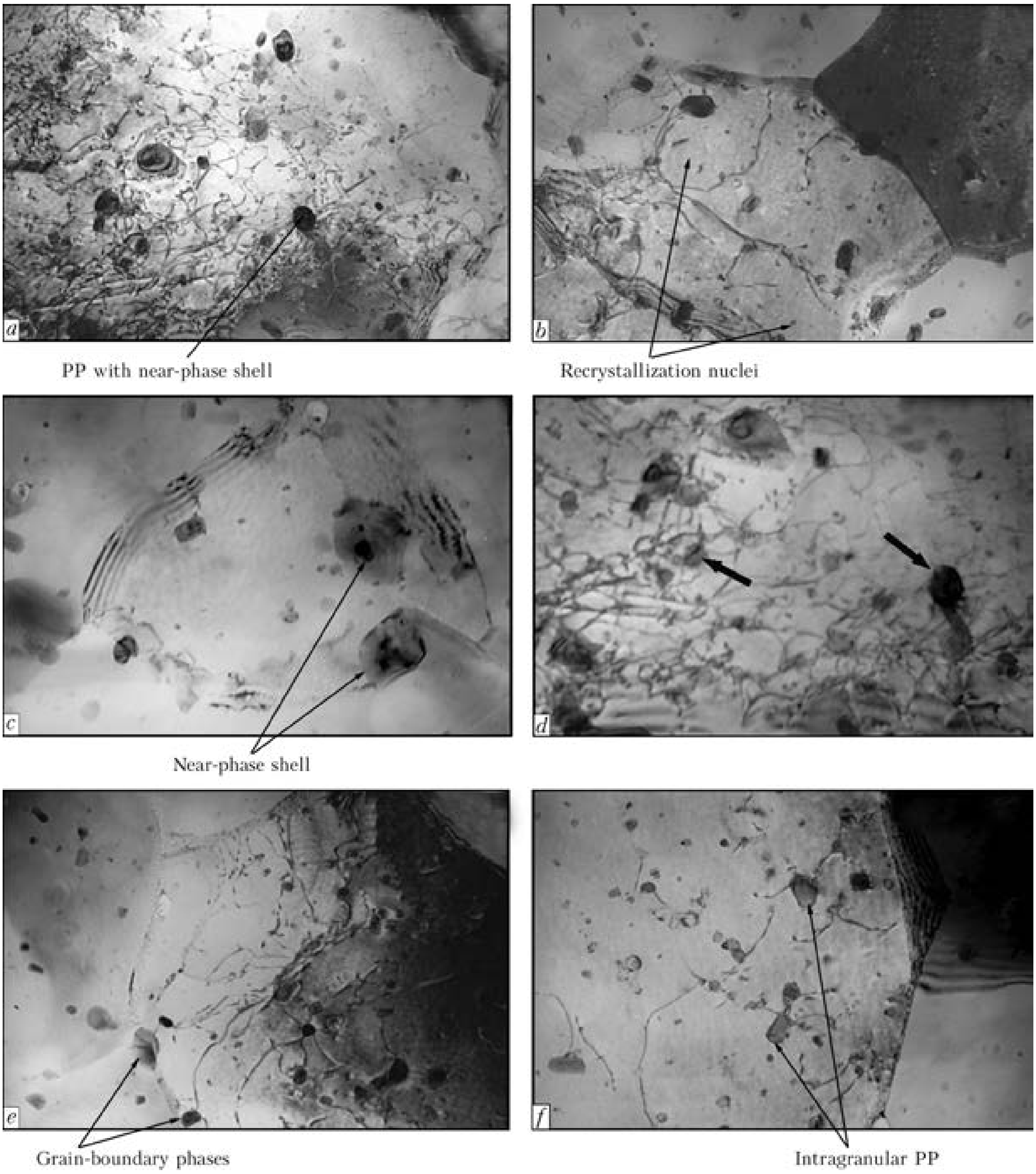

Figure 4. Microstructures of weld metal of 1460 alloy made by FSW: *a*, *d* — dislocation distribution; *b*, *c*, *f* — PP distribution in grain bulk; *e* — same, but in grain-boundary zones of weld metal (*a*, *c*, *d*, *f* — ×30000; *b*, *e* — ×20000)

location density in the metal of welds in fusion welding (Figure 4, *a*). Increase of intragranular dislocation density is accompanied by active redistribution of dislocations, that is indicated by formation of substructural elements — blocks, fragments, etc. (Figure 4, *b*).

Apparently, structure refinement and activation of dislocation redistribution under FSW conditions are due to intensive deformation of weld metal heated up to plastic state and prevalence of deformation-activated processes in structural changes (dynamic recrystallization) over thermally activated processes (collective recrystallization).

The features of structural state of weld metal obtained in the solid phase by FSW (compared to metal of welds made by TIG welding) are a considerable (by 2–5 times) refinement of PP (dimensions of this PP type are in the ranges of 0.06–0.40 μm) and considerable increase of their quantity at uniform distribution, occurring in all the zones of weld metal — both in intragranular and in grain-boundary volumes (see Figure 4). The latter is, apparently, related to breaking up of intravolume and grain-boundary eutectic coarse phase, characteristic for weld metal obtained by TIG welding. It should be noted that the majority of PP forming in the weld metal

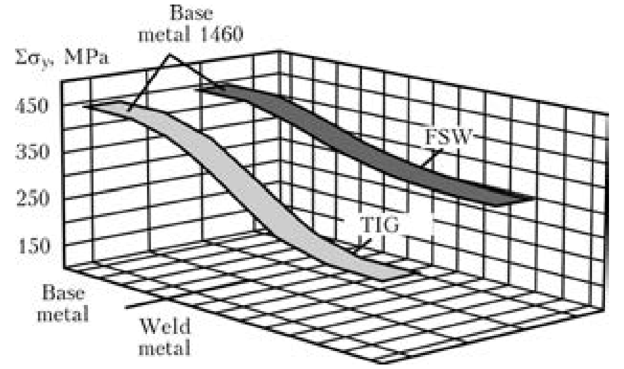

Figure 5. Total integral value of yield limit $\Sigma\sigma_y$ of aluminium alloy 1460 in different zones of the joint (base metal and metal of welds made by TIG welding and FSW)

under FSW conditions are surrounded by a near-phase shell (see Figure 4, *c*), that is indicative of intensive alloying of the local near-phase space in matrix grain bulk.

Analytical assessment of the change of welded joint properties. Proceeding from comprehensive experimental investigations of structural-phase components forming in the metal under different thermodeformational conditions, analytical assessment of their specific (differentiated) contribution to the change of general (integrated) values of such a mechanical characteristic as yield limit σ_y of base and weld metal after cardinally differing welding processes, namely TIG (argon-arc) welding and solid-phase FSW was performed.

Analytical assessments of σ_y were performed by Archard equation, including known Hall-Petch, Orowan and other dependencies [4–11]:

$$\Sigma\sigma_y = \Delta\sigma_0 + \Delta\sigma_{s.s} + \Delta\sigma_{gr} + \Delta\sigma_s + \Delta\sigma_d + \Delta\sigma_{d.s},$$

where $\Delta\sigma_0$ is the metal lattice resistance to free dislocation motion (lattice friction stress or Peierls–Nabarro stress); $\Delta\sigma_{s.s}$ is the solid solution strengthening by alloying elements and impurities (solid solution strengthening); $\Delta\sigma_{gr}$, $\Delta\sigma_s$ is the strengthening due to the change of grain and subgrain size (Hall–Petch dependencies, granular and subgranular strengthening); $\Delta\sigma_d$ is the dislocation strengthening due to interdislocation interaction; $\Delta\sigma_{d.s}$ is the strengthening due to dispersed particles by Orowan (dispersion strengthening).

General value of yield limit $\Sigma\sigma_y$ is given in Figure 5, specific contribution $\Delta\sigma_y$ of various structural components to the above-mentioned characteristic of base metal and weld metal, produced by various welding processes, is shown in Figure 6.

It is found that in the base metal of 1460 alloy the most significant contribution among the structural-phase components determining the yield limit values, should be made by: dislocation component ($\Delta\sigma_d$ = 127 MPa), subgrain ($\Delta\sigma_s$ = = 151 MPa) and grain strengthening ($\Delta\sigma_{gr}$ = = 62 MPa) (Figure 6, *a*), that, taken as percentage of the general value of yield limit, is equal to 14, 28 and 33 %, respectively (Figure 6, *b*).

In fusion welding the contribution of the above components decreases significantly, as dislocation density in the metal of such welds drops abruptly, whereas grain size increases considerably, resulting in the assessed characteristics of

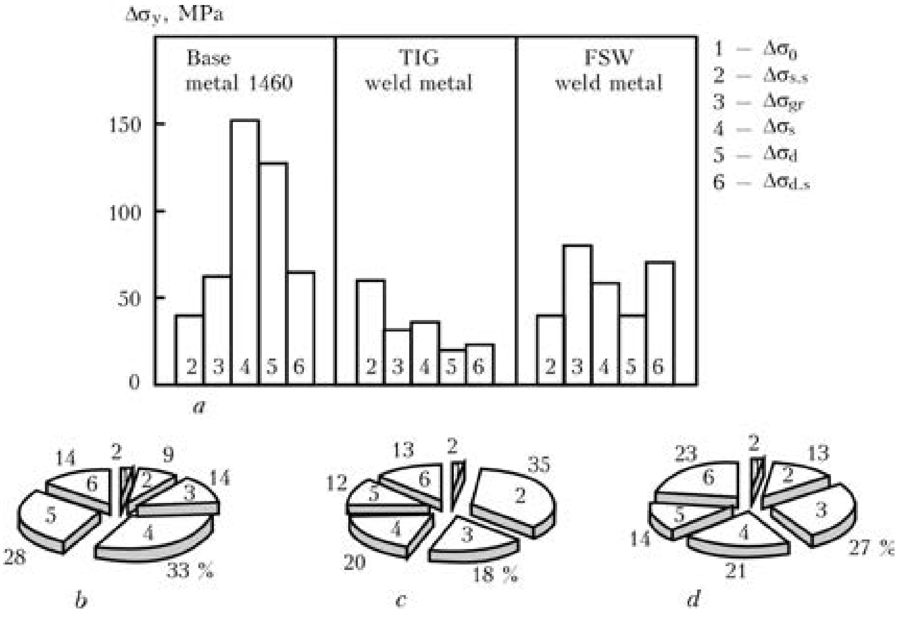

Figure 6. Histogram of differentiated contribution of structural-phase components of $\Delta\sigma_y$ into calculated value of yield limit (*a*), and sector diagrams (*b*–*d*) of structural contribution (solid solution, grain, subgrain, dislocation, dispersion) into the total value of yield limit $\Sigma\sigma_y$ in base metal (*b*) and metal of welds made by TIG welding (*c*) and FSW (*d*)

weld metal decreasing by 2–5 times in fusion welding compared to base metal, namely to the following values: $\Delta\sigma_d = 20$, $\Delta\sigma_s = 36$, $\Delta\sigma_{gr} = 31$ MPa. Percentagewise, the contribution of the respective structures is equal to 12, 20 and 18 %, respectively (Figure 6, *a*, *c*). Here, solid solution strengthening $\Delta\sigma_{s.s}$ in the above type of weld metal is equal approximately to 60 MPa, i.e. 35 %.

In welds produced in the solid phase by FSW, compared to welds made by fusion welding, a significant increase of the yield limit values will be promoted by: significant refinement of the structure ($\Delta\sigma_{gr} = 80$ MPa), formation of substructure ($\Delta\sigma_s = 58$ MPa), increase of dislocation density (dislocation strengthening $\Delta\sigma_d = 40$ MPa) and significant increase of bulk density of dispersed and uniformly distributed PP ($\Delta\sigma_{d.s} = 70$ MPa), that percentagewise in the general (integral) value of $\Sigma\sigma_y$ is equal to, respectively, 27, 21, 14 and 23 % (Figure 6, *a*, *d*). Under FSW conditions this allows leveling the gradients of strength characteristics (in this case — the yield limit) between the base, i.e. metal welded and weld metal to values of the order of 156 MPa that is much less than the gradient (of the order of 285 MPa) usually found in fusion welding.

Conclusions

1. Integrated methods of investigation of welded joints of complex-alloyed aluminium alloy 1460 were applied to determine the changes of key structural-phase components, affecting the mechanical characteristics of welded joints at the change of conditions of technological modes of welding processes — from TIG welding to FSW (solid phase welding).

2. Under the conditions of fusion welding, the metal of welds is characterized by a coarse-grained structure, lowering of total bulk density of dislocations, formation of globular intragranular and extended intergranular PP of eutectic type that is due to prevalence of thermal activation of relaxation processes.

3. Weld metal structure in FSW features an abrupt refinement of the grain that is associated with activation of the nucleation processes, increase of the total dislocation density, as well as significant PP dispersion at their uniform distribution in intragranular and grain boundary volumes, that is ensured by prevalence of thermodeformational conditions at formation of structural-phase state of weld metal.

4. Analytical assessment of the general (integral $\Sigma\sigma_y$) value of the yield limit showed that in the metal of welds made by FSW a total increase of $\Sigma\sigma_y \sim 40$ % is observed due to refinement of grain ($\Delta\sigma_{gr} \leq 27$ %) and subgrain ($\Delta\sigma_s \leq 21$ %) structures and PP dispersion ($\Delta\sigma_{d.s} \leq 23$ %), that considerably reduces the gradient of mechanical characteristics between the base metal and weld metal. Contrarily, lowering of yield limit value $\Sigma\sigma_y$ of weld metal in fusion welding, which is due to coarsening of the grain structure and lowering of general density of dislocations promotes at increase of the gradient by the indices of yield limit between the base metal and metal of welds of the welded joint.

1. Fridlyander, I.N. (2000) Aluminium alloys in flying vehicles in the periods from 1970 to 1999 and from 2000 to 2015. In: *Proc. of 5th Session of Sci. Council on Advanced Materials of IAAS on Problems of Current Materials Science*. Kiev: Naukova Dumka.
2. Fridlyander, I.N. (1998) Aluminium alloys in aeronautical engineering. In: *Proc. of 3rd Session of Sci. Council on Advanced Materials of IAAS on Problems of Current Materials Science*. Kiev: Naukova Dumka.
3. Darovsky, Yu.F., Markashova, L.I., Abramov, N.P. et al. (1985) Procedure of thinning of dissimilar welded joint specimens for electron microscopic examinations. *Avtomatich. Svarka*, **12**, 60.
4. Suzuki, H. (1967) *About yield strength of polycrystalline metals and alloys*. Moscow: Metallurgiya, 255–260.
5. Ashby, M.F. (1972) On Orowan stress. In: *Physics of strength and ductility*. Moscow: Metallurgiya.
6. Goldshtejn, M.I., Litvinov, V.S., Bronfin, B.M. (1986) *Physics of metals of high-strength alloys*. Moscow: Metallurgiya.
7. Conrad, H. (1973) Model of deformation strengthening to explain the grain size influence on metal yield stress. In: *Ultrafine grain in metals*. Ed. by L.K. Gordienko. Moscow: Metallurgiya, 206–219.
8. Armstrong, R.V. (1973) Strength properties of ultrafine grain metals. *Ibid*., 11–40
9. Petch, N.J. (1953) The cleavage strength of polycrystalline. *J. Iron and Steel Inst*., 173(**1**), 25-28.
10. Orowan, E. (1954) *Dislocation in metals*. New York: AIME.
11. Ashby, M.F. (1983) Mechanisms of deformation and fracture. *Adv. Appl. Mech*., **23**, 117–177.

Received 15.01.2013