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INFLUENCE OF TOOL SHAPE FOR FRICTION STIR WELDING ON PHYSICOMECHANICAL PROPERTIES OF ZONES OF WELDS OF ALUMINIUM ALLOY EN AW 6082-T6

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The paper presents the results of studying the formation of macrostructure and distribution of mechanical properties in welded joints of flat specimens from aluminium alloy EN AW 6082-T6 of 8 mm thick, produced by the method of friction stir welding with application of three types of specially designed pins with collars: C — cylindrical threaded pin and collar with a spiral groove; T—cylindrical threaded pin with three grooves and collar with a spiral groove; S — smooth cylindrical pin without thread and flat collar. Friction stir welding was performed in the equipment of the Institute of Welding in Gliwice (Poland), and treatment and mechanical tests were conducted at the E.O. Paton Electric Welding Institute of the NAS of Ukraine. Mechanical testing by indentation was performed in Micron-gamma device, which allows experimental identification of structural state of metal after refinement and determination of the strain hardening presence by limiting values of ratio of hardness to Young's modulus of elasticity. It was found that for all three specimens the HAZ hardness decreases, and in the zone of thermomechanical effect the hardness increases. Maximum hardness values are inherent to the central part of welded joint nugget, as well as to light-coloured oval concentrated fragments of structure in the nugget upper and lower part. Judging by the presence of nanosized hardened structure and uniformity of its distribution in the nugget, as well as good dispersion of oxide films and absence of discontinuities, the friction stir welding with C-type tool can be regarded as the optimum variant. An assumption was made that formation of a uniform structure in welds can be achieved at three-four rotations of the tool in friction stir welding in one place. 21 Ref., 1 Table, 7 Figures.

Keywords: *friction stir welding, zone of thermomechanical effect, weld nugget, indentation, Berkovich indenter, Young's modulus*, *physicomechanical properties*

The technology of friction stir welding (FSW) is used to join different alloys of magnesium, copper, titanium, zinc and even steel, but the main industrial application of FSW is for butt joining of long-length parts of aluminium alloys (about 99 % of all joints). The characteristics of FSW technology and its advantages associated with a particular type of joints or application are the subject of numerous publications [1–11]. In general, during FSW, a rotating tool equipped with a pin and a collar, is slowly submerged between the edges of the elements being joined (touching each other) and moved along the welding line [5]. The heat, necessary for plasticizing the material, is generated by friction between the tool and the materials being joined, the rotational and translational movement of the pin provides an intense plastic deformation of the heated softened material to move from the tip of the pin to the collar, creating a permanent structure of a joint on both sides of materials being joined.

The basic technological parameters of the FSW process are the following: speed of tool rotation and rotation direction, rpm; linear welding speed, mm/min; inclination angle of the tool relative to the surface of elements to be welded, deg; type of tool and its dimensions: diameter of the pin and diameter of the collar, mm [10].

The key parameter, that determines the quality standard of FSW joints is the pin geometry for mixing, which determines different conditions of local heating and mutual mass transfer of the metal of elements, being joined. In addition to the pin, an important element of FSW tool is the collar, the main function of which is the heat generation due to friction between the collar and materials being welded, pressure transfer and formation of deformations in the weld surface area.

It is believed that after intense twisting plastic deformation in the nugget of FSW weld, a change in the nature of interatomic interactions and the formation of a structure, close to nanosized, occurs. Alongside with the formation of nanostructures, the formation of metastable states, supersaturated solid solutions and metastable phases can occur. Also, due to large deformations of the material of both edges of parts welded, the thermomechanical zone may contain a highly fragmented and disoriented structure of the recrystallized amorphous state. All this inevitably affects the physical and chemical properties of the joint zone.

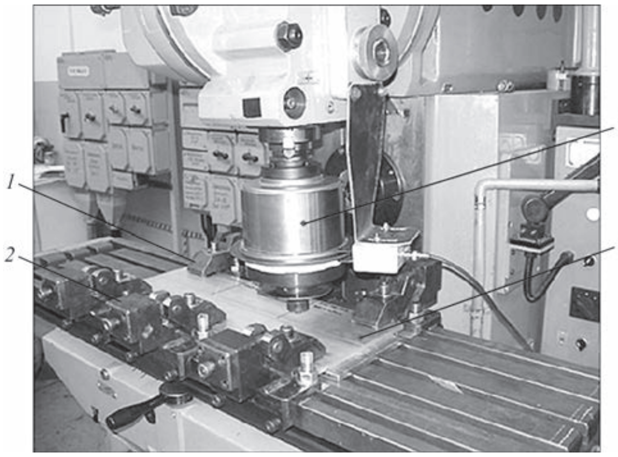

Figure 1. Type of installation for friction stir welding: *1* — tool; *2* — fastener; *3* — unit for tool fixation; *4* — parts to be welded

Therefore, it is of interest to study the dependence of the influence of the key parameter of the FSW: the welding tool geometry on the formation of nano-dispersed zones of welds with minimal defectiveness and uniform structure, which should positively affect the strength of welded joint as a whole.

The aim of this work is to determine the optimal shape of FSW tool based on the results of a local study of structure and physical and mechanical properties of zone of thermomechanical effect in welds, made using three types of specially designed pins with collars. In order to solve this aim, a joint investigation was carried out: FSW was carried out in the equipment of the Institute of Welding in Gliwice, and the treatment and mechanical tests of specimens were performed at the E.O. Paton Electric Welding Institute of the NAS of Ukraine. From the results of mechanical tests and the ratio of hardness to Young's elasticity modulus, the structural state of weld zones was experimentally identified.

Equipment, materials and investigation methods. FSW was carried out in a modified milling installation FYF32JU, equipped with a gripping system and a measuring head for control of welding process parameters (Figure 1).

For welding, specimens of aluminium alloy 6082-T6 (analogue of AD35) were selected in the form of flat hot-rolled rods of 10 cm long and 0.8 cm thick. Heat treatment of the alloy was carried out at a temperature of about 540 °C with the following artificial aging at 170 °C. The chemical composition is presented in Table.

FSW tools of three types (Figure 2) were specially made of high-speed, high-strength (for twisting) alloyed steel HS6-5-2 of increased wear resistance up to 600 °C. According to the type of geometric features, they are classified as follows:

- C is an ordinary tool of the «conventional» type, consisting of a body, a cylindrical threaded pin and a collar with a spiral groove;
- T is a tool of the «triflute» type, consisting of a body, a cylindrical threaded pin with three grooves and a collar with a spiral groove;
- S is a «simple» tool, consisting of a body, a smooth cylindrical pin without a thread and a flat collar.

The process of FSW was performed in the following mode: speed of tool rotation — 710 rpm; linear welding speed — 900 mm/min; tools of the type C, T and S with a pin length of 7.8 mm; inclination angle of the tool with respect to welded workpieces is 1.5°; direction of rotation of the tool is clockwise. The mentioned parameters provide the most economical process in terms of welding speed. After welding, each weld passed visual inspection for compliance with the standard with a positive result.

For optical examination of macrostructure of FSW joints, thin sections were prepared using a standard method for aluminium alloys: the surfaces of specimens were grinded in the machine-tool 3E88IM with an abrasive paper of different grain sizes (P120 — 100–125, P240 — 50–63, P600 — 20–28, P1200 — 10–14 μm), polished with paste GOI to a mirror shine, washed with water and alcohol, dried with a filter paper. Etching of a structure was performed with a reagent of 5 ml of HNO_3, 30 ml of CH_3COOH, 300 ml of H_2O.

For mechanical indentation tests, the device Micro-gamma was used (Figure 3, *a*), designed in the laboratory of nanotechnology of the Aerospace Institute of the National Aviation University of Ukraine. Indentation is the test based on the method of Oliver and Pharr [13–16] for determination of hardness H and elasticity modulus *E* according to indentation diagrams, which are

Chemical composition of aluminium alloy 6082, wt.% [12]

Alloy	Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Al
6082	0.7–1.3	Up to 0.5	0.1	0.4–1.0	0.6–1.2	Up to 0.25	Up to 0.2	Up to до 0.1	Rest

Figure 2. Tools for friction stir welding: *a* — type C; *b* — T; *c* — S

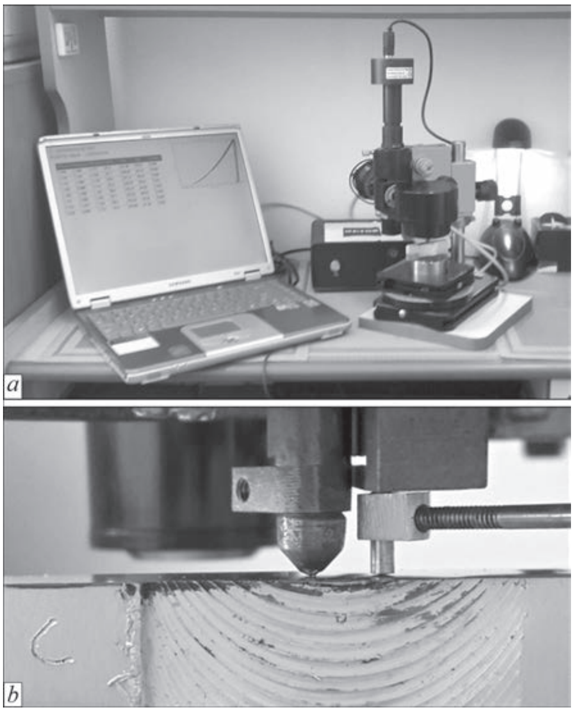

Figure 3. Device «Micron-gamma» (*a*) in the process of recording diagram of continuous indentation of the indenter into the material (*b*)

fixed at continuous pressing-in of a diamond trihedral pyramidal indenter of Berkovich [17, 18] in accordance with ISO/FDIS 14577-1:2015; Metallic materials — Instrumented indentation test for hardness and materials parameters — Part 1: Test method (ISO Central Secretariat, Geneva, Switzerland). The indentation was carried out on the polished surface of specimens without etching at 100 g loading of indenter (Figure 3, *b*).

Based on the ratio H/E, the structural state of metal was identified experimentally after grinding, and the presence of strain hardening was determined. It is known that all materials in a different structural state, depending on the ratio of hardness to elasticity modulus (H/E) can be placed in a row, including three groups [19–21]. The first group is coarse-crystalline ($H/E <$ < 0.04), the second is fine-crystalline and nanomaterials ($H/E \approx 0.05$–0.09) and the third group is materials in the amorphous and amorphous-crystalline states

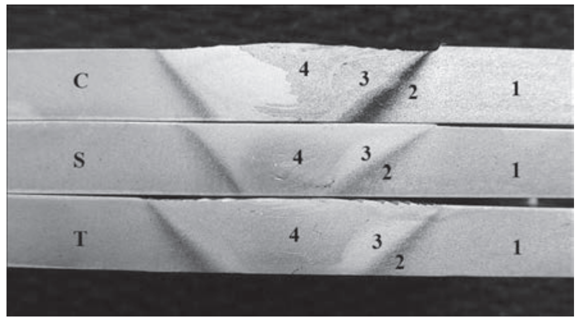

Figure 4. Macrostructure and zones of FSW joints of aluminium alloy EN AW 6082-T6 of 0.8 cm thickness (1–4, see description in the text)

($H/E \geq 0.1$). The establishment of limiting values for H/E for different structural states facilitates identification of a material with an unknown structural state.

Results and discussion. The asymmetrical sides of «running-on» (AS) and «running-out» (RS) observed in the FSW welds (Figure 4) are predetermined by the asymmetry of metal twisting deformation and are related to the asymmetry of finding the initial point of tool touching at increasing pressure, and consequently, with the difference in distribution of temperature fields of heating at intensive mechanical effect.

Typical for all three FSW specimens is the formation of a nugget zone in the centre of joints, which contains oval concentric fragments, differing in structure. The formation of oval rings is associated with the peculiar features of metal mixing with different tool tips. A complex profile adjoins the nugget, which forms the weld upper part. As a result of etching sections, defects of joints were distinguished in the form of local discontinuities and cavities along the line separating the nugget centre from its surrounding zone of thermomechanical effect. These bands of aluminium oxide are inherent to the surfaces of materials being welded, because they were not sufficiently mechanically distributed by the welding tool. This type of defect is typical for FSW welds and depends on linear welding speed, i.e., with an increase in the linear welding speed, the dispersion of oxides during mechanical mass transfer is increased and the number of defects is decreased.

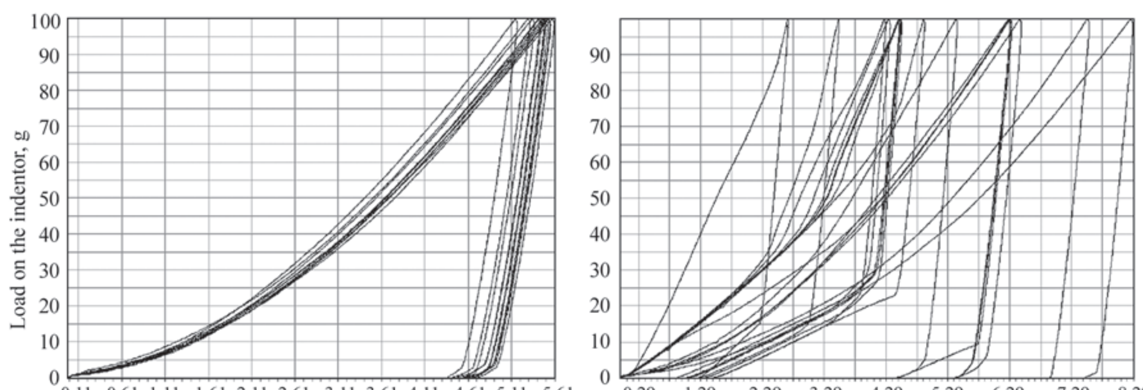

Figure 5. Difference in diagrams of base metal indentation (*a*) and different heat-affected zones of S-type specimen (*b*)

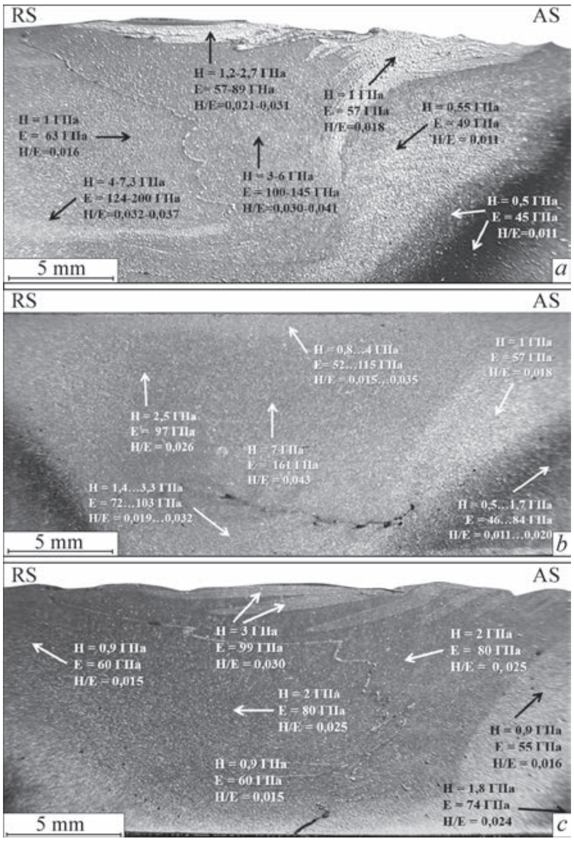

Figure 6. Distribution of hardness *H*, elasticity modulus *E* and resistance to deformation *H/E* in the microstructure of FSW weld of a tool of C-type (*a*); S-type (*b*); T-type (*c*)

Another typical horizontal defect, caused by insufficient mixing of materials, is observed in a specimen produced using a smooth tool of S-type without thread on the tool pin. The cause for such a defect is that the flat surfaces of tool during friction lead to local overheating of metal up to the melting temperature.

Thus, in the welded joint, four zones specific for FSW are formed: directly to the zone 1 (base metal — BM) the zone 2 is adjoined, where the metal of workpieces remains nondeformed and changes its structure only under the influence of heating (heat-affected zone — HAZ); zone 3, where the metal is subjected to significant plastic deformations and heating (zone of thermomechanical effect — ZTME) and zone 4 — is the joint nugget, where dynamic recrystallization occurs.

The mechanical test showed a fundamental difference for FSW welds in the diagrams of base metal indentation (Figure 5, *a*) and of different zones (Figure 5, *b*), which characterizes the presence of a modified structural state.

For all three specimens, the hardness of zone 2 (HAZ) is reduced. The maximum values of hardness are characteristic for the zone 4, the central part of the nugget (Figure 6), as well as for bright oval concentric fragments of the structure of the upper and lower parts of the nugget (Figure 6, *a*, *c*). The averaged values of physicomechanical properties of three types of FSW joints are as follows:

- zone 1 (BM) — H = 1.2 GPa, E = 70 GPa;
- zone 2 (HAZ) — H = 0.5–1.0 GPa, E = 45–57 GPa;
- zone 3 (ZTME) — H = 1.0–3.0 GPa, E = 63–103 GPa;
- zone 4 (nugget) — H = 2.0–7.0 GPa, E = 80–161 GPa.

Figure 6, *b* shows welded joint, produced by a tool of C-type with a cylindrical threaded pin and a collar with a spiral groove, which contains the maximum hardness value of 7.3 GPa for all three specimens (light oval fragment of the lower part of the nugget), also the maximum values of E to 200 GPa and the ratio of H/E to 0.041. Such values fix the presence of a nanodispersed multiphase structure formed at the highest degree of deformation. A similar structure is also characteristic for the 4th zone of nugget of FSW welds: for C-type H/E to 0.041; for S-type H/E to 0.043 at the initial polycrystalline structural state of the base metal H/E = 0.017. Such hardening during refinement of the structure grains is usually associated with a decrease in the density of dislocations and their braking.

Thus, if one considers the presence of a nanosized hardened structure in the weld produced by FSW and the uniformity of its distribution, good dissipation of oxide films and the absence of discontinuities as ad-

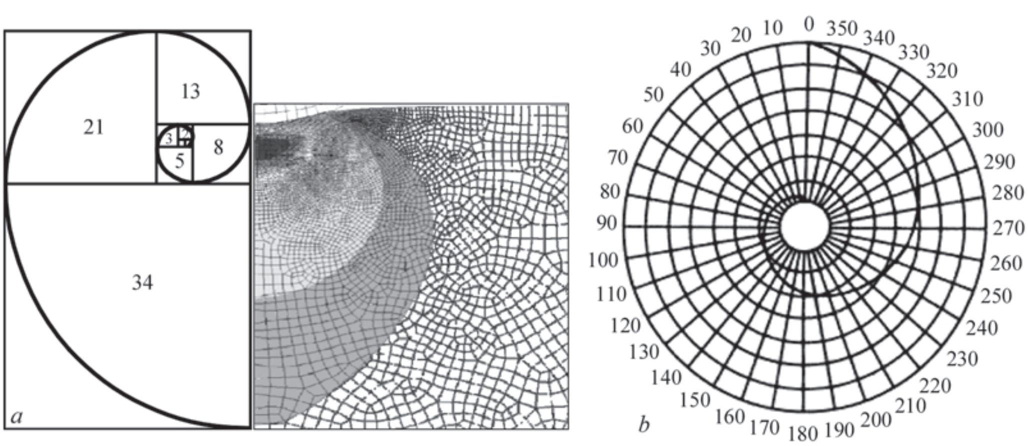

Figure 7. Fibonacci spiral and FSW model with a large-scale change in the structure fragments (*a*) and radial change in the structure segments during twisting (*b*)

vantageous, then a tool of C-type is optimal in this investigation.

In the course of the work, it was assumed that according to the degree of refinement of grains of the metal structure to nanosizes at a twisting deformation, it is possible to determine the number of tool rotations for FSW in one place. If the twisting deformation is considered in the form of a spiral mathematical Fibonacci proportion — 1, 2, 3, 5, 8, 13 ... (Figure 7, *a*), where a full revolution (unwinding) is a sequence of four values, then, in the opposite direction (twisting) of a spiral, a substantial structural refinement will take place already after deformation by a half-revolution of 0...180° (Figure 7, *b*), and to create a homogeneous nanostructure, deformation by several revolutions is required.

Taking the averaged grain diameter of the refined structure as 100 nm, and the averaged grain diameter of the initial polycrystalline aluminium: 100 000 nm (0.1 mm), this ratio will be 1:1000. Then, refinement of grain in such an inverse proportion will occur at three or four revolutions of the FSW tool in one place:

- 1st revolution — 1597, 987, 610, 377;
- 2nd revolution — 233, 144, 89, 55;
- 3rd revolution — 34, 21, 13, 8;
- 4th revolution — 5, 3, 2, 1.

Technologically, this can be controlled by changing the speed of revolutions and/or linear speed of the tool movement during welding, but usually the welding equipment has a fixed speed, which limits the control.

Conclusion

The physicomechanical properties of welds of joints from aluminium alloy EN AW 6082-T6, produced by friction stir welding with the use of three tools of different geometric shapes, were investigated. For all three specimens, the hardness of heat-affected zone decreases, and in the zone of thermomechanical effect the hardness increases. The maximum values of hardness are typical for the central part of the nugget of welded joints, as well as for light oval concentric fragments of structure of the upper and lower parts of the nugget. By the presence of a nanosized hardened structure and the uniformity of its distribution, as well as good dissipation of oxide films and the absence of discontinuities in the nugget of welds, the FSW tool of C-type is optimal. It was assumed that the formation of a uniform structure in welds can be obtained at three or four revolutions of the FSW tool in one place.

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