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Relation between geometry of FSW tools and formation of nano- dispersed zones in macrostructure EN AW 6082-T6 alloy welded joints

Abstract: An article present the result of macrostructure formation with distribution of mechanical properties in cross-sections of 8 mm-thick one-sided butt-welded FSW joints of EN AW 6082-T6 alloy which were obtained using three types of specially designed tools: C-type – conventional tool consisting of a housing, cylindrical threaded probe and a shoulder with a grooved spiral, T-type – Triflute-type tool consisting of a housing, cylindrical threaded probe with three grooves and a shoulder with a grooved spiral, S-type – simple tool consisting of a housing, smooth cylindrical probe without a thread and a flat shoulder. Friction stir welding was performed using equipment of the Institute of Welding in Gliwice of Poland, and mechanical tests in the E.O. Paton Electric Welding Institute of the NAS of Ukraine. Mechanical test by indentation was performed using Micron-gamma device, which allows experimental identification of structural state of metal 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 revolutions of the tool in friction stir welding in one place. The model of thermal fields distribution in Al-plate during FSW using a C-type tool visualized the metal's thermal condition when formated hardened nano-dispersed weld zones.

Keywords: friction stir welding, FSW, thermomechanical affected zone, weld core, indentation, Berkovich indenter, hardness, Young's modulus

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Introduction

The technology of friction stir welding (FSW) is used to join various alloys of magnesium, copper, titanium, zinc and even steel, but the main industrial application is for butt joining lengthy parts made of aluminum alloys (about 99% of all joints). The characteristics of the FSW technology and its advantages related to specific type of joints or application have been a subject of numerous publications [1–10]. In the general scheme of FSW the rotating tool slowly sinks between the edges of the elements to be joined (touching each other) and moves along the welding line (Fig. 1). The heat required for plasticifation of the material is generated by friction between the tool and the materials being joined, the rotational and translational motion of instrument provides intense plastic deformation of the heated softened material to move from the tip of the probe to the shoulder, creating a continuous joint structure on both sides of the materials being joined.

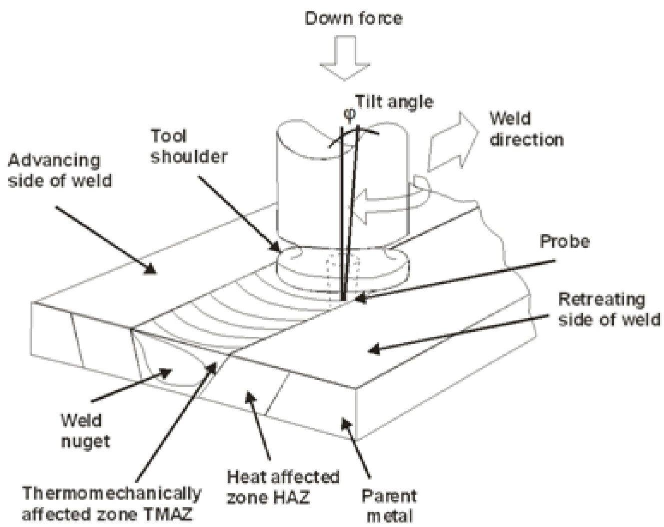

Fig. 1. Scheme of FSW process [10]

The basic technological parameters of the FSW process include: – rotational speed of the tool and sense of rotation (rev/min.), tool inclination angle in relation to the surface of welded elements (°); type of tool and its dimensions – probe diameter (mm), shoulder diameter (mm) [10].

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

The main advantages of FSW process there is the absence of melt of metal and defects caused by solidification of liquid metal, defects in the form of a dendritic structure, shrink holes, poor penetration, slag inclusions, accumulations of gas pores, etc. This is due to the nature of the mass transfer of the material as a result of the frictional interaction of the tool and the metal in contact with it. However, the formation of defects is possible at the interface between the base metal and the flow layer, which leads to the formation of a layered structure. The main reason for the formation of layers is the competition of strain hardening and softening due to frictional heating and heat caused by deformation. As a result, a metal layer is formed with the same degree of deformation, whereas at its border with the underlying material there is a minimum value of the yield strength, which leads to plastic shear of the entire layer relative to the substrate. The above process is repeated many times - the deformation is accompanied by hardening of the material at the interface and the release of heat, which leads to the formation and shear of the underlying layer. Thus, the thickness of the deformed layer increases abruptly at high speed.

The most reliable explanation for the formation of a layered structure during FSW can be the approach taken when considering the sliding friction of metals. The upper layer of the material near the surface under dry friction with high loads, experiences the same effect as the weld zone undergoes during FSW. Mechanical contact with the counter body leads to frictional heating of the surface, weakening and severe plastic deformation of the material in cramped conditions. As a result of energy dissipation during plastic deformation, intense heat release occurs in the bulk of the material, which leads to increasing of plasticization. Moreover, under the conditions of super plasticity, near-surface layers are formed with a structure and properties that differ from the properties of the base material.

The characteristic structure of the surface layer formed by successive local shearing of the material layers during sliding friction of metals is similar to observed in welds of FSW. However, the peculiarities of the plastic flow of the metal in the process of MTP create the prerequisites for the formation of defects in the structure of the weld. Some defects at the interface of the weld and the base are similar to those formed during sliding friction as a result of incompatibility of deformations of the boundary layer and the base material, but there are also those caused by the mass transfer characteristics of the metal during the FSW process due to the tool geometry and technological parameters [11].

The size of the deformable zone, the degree and speed of mixing of the material, temperature, dimensions and features of the microstructure formed in the weld and consequently, the processes of formation of defects are determined by the properties of base metal, as well as the technological parameters of FSW process. Therefore, in the technological implementation of FSW an important task is to study the mechanisms and identify the physical laws of the formation of the structural state and the factors leading to the formation of structural heterogeneities. Having knowledge of the mechanisms of formation of the structural state in the weld zone and near-weld zone and the causes of defects in a particular material and their relationship with the conditions of thermomechanical effects, one can purposefully control the welding parameters to obtain defect-free welded joints obtained by a modern and cost-effective welding method.

It is known that after intense twisting plastic deformation in the core of the welds there is a change in the character of interatomic interactions and the formation of a close to nano-sized structure. Along with the formation of nanostructures, the formation of metastable states, solid solutions and metastable phases can occur. Also, due to large deformations of the material of both edges of the parts to be 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. Therefore, it is of interest to study the dependence of the influence of the key FSW parameter – the geometry of the welding tool on the formation of nano- dispersed zones in welds with minimal defects and uniform structure, which should positively affected on welded joint's strength a whole.

The aim of work – based on local study of weld's structure and physic-mechanical properties to determine optimal one of used three FSW instruments. To solve this goal, a joint study was carried out – friction stir welding was performs by equipment of the Polish Institute of Welding in Gliwice, and samples processing and mechanical tests were carried at the E. Paton Electric Welding Institute of the National Academy of Sciences of Ukraine. According to the data results of mechanical test and using ratio of hardness to Young's modulus of elasticity, the structural state of the weld zones was experimentally identified.

Material and experimental procedure

The material used in tests was aluminium alloy 6082-T6 in the form of flat hot rolled bars of dimensions 100×8 mm. The chemical composition of aluminium alloy 6082 is presented in Table 1. The heat treatment of the alloy was comprised of solutionising at about 540°C following by artificial aging at 170°C. The FSW joints were made as 8 mm-thick one-sided butt-welded joints (produced with a one-sided run of the tool).

Table 1. Chemical composition of aluminium alloy 6082 (wt. %) [12]

Alloy	Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Al
6082	0.7-1.3	max 0.5	0.1	0.4-1.0	0.6-1.2	max 0.25	max 0.2	max 0.1	rest

Three tools, with different probe shapes and shoulder surfaces, were used in the experiments. The tools were made of HS6-5-2 high-speed steel. The steel exhibits high torsional strength and abrasion resistance up to a temperature of 600°C.

The following tools were (Fig. 2) used for FSW process:

- C-type tool – conventional tool consisting of a housing, cylindrical threaded probe and a shoulder with a grooved spiral,
- T-type tool – Triflute-type tool consisting of a housing, cylindrical threaded probe with three grooves and a shoulder with a grooved spiral,
- S-type tool – simple tool consisting of a housing, smooth cylindrical probe without a thread and a flat shoulder.

To produce specimens for experimental tests the FSW process was carried out at the following welding conditions:

- tool rotational speed – 710 rev./min,
- linear welding speed – 900 mm/min,
- tool – C-type tool, T-type tool, S-type tool (the length of the probe was equal to 7.8 mm),
- angle of tool inclination in relation to the welded blanks – 1.5°,
- direction of tool revolutions – clockwise.

The aforesaid parameters ensured the most economical welding process (from welding speed point of view).

Production of test joints were conducted on conventional milling machine type FYF32JU equipped with grip system and measurement head to monitor parameters during welding process (Fig. 3). After welding each joint were visually inspected with positive result.

For the optical study macrostructure of the cross-section of FSW joints the samples were prepared according to the standard for aluminum alloys procedure - the surfaces were ground on a 3E88IM machine with sandpaper of different grain sizes (P120 100-125 μm, P240 50-63 μm, P600 20-28 μm, P1200 10-14 μm), polished with chromium (III) oxide Cr2O3 green paste to a mirror finish, washed with water and technical alcohol, dried with filter paper. The colored structures were etched with a reagent of 5 ml of HNO3, 30 ml of CH3COOH, 300 ml of H2O.

„Micro-gamma" device (Fig. 4a) developed at the nanotechnology laboratory of the Aerospace Institute of National Aviation University of Ukraine were used for mechanical indentation tests. Indentation test due to ISO / FDIS 14577-1: 2015; „Metallic materials - Part 1: Test

Fig. 2. Schematic view of FSW tools

Fig. 3. View of FSW station in Institute of Welding

Fig. 4. The device "Micron-gamma" (a) in the process of recording the diagram of continuous indentation of the indenter into the material (b)

method" is based on Oliver and Farr's method [13] for determining hardness (H) and modulus of elasticity (E) by diagrams of displacement versus load of Berkovich indenter [14–16]. Using H/E ratio were identifying the structural condition of metal in welds and presence of strain hardening. It is known [17] that according to such ratio all materials in a different structural state can be ranged in three groups: first group is large-crystalline (H/E <0.04), the second is fine-crystalline and nanomaterials (H/E 0.05–0.09) and the third group is materials in amorphous and amorphous-crystalline states (H/E 0.1). The founded limit values of H/E for various structural states facilitates the identification of a material with an unknown structural state. Indentation was carried on the polished samples surfaces without etching under 100 g loading on indenter (Fig. 4b).

Using the heat transfer module of COMSOL® Multiphysics software was evaluated the heat distribution in FSW weld using the C-type tool. Assuming that heat dissipation completely stops when the temperature reaches the melting point of aluminium since friction between the pin and the Al-plate decreases after reaching this point. The model is built of only one Al-plate due to the symmetry with respect to the weld and the high rotation speed.

Results and discussion

The asymmetrical "advanced" (AS) and „retreating" (RS) sides observed in the FSW welds (Fig. 5) are due to the asymmetry of the metal's twisting deformation and are related to the asymmetry of finding the initial point of tangency of the tool with increasing pressure, and consequently, with the difference distributions of temperature fields of heating with intensive mechanical action.

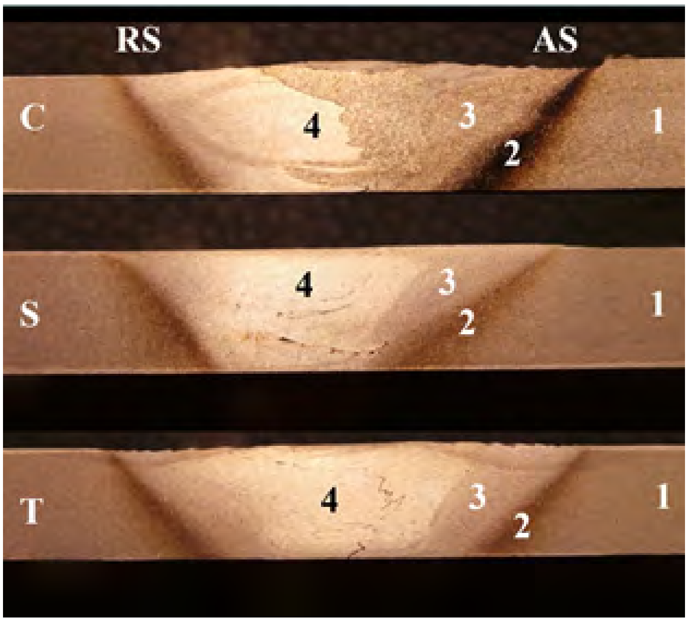

Fig. 5. Cross-sections of 8 mm-thick one-sided butt-welded FSW joints of EN AW 6082-T6 alloy were obtained by three types of tools

Typical for all three samples is the formation of a core zone in the center of FSW joints, which contains oval concentric fragments that differ in structure (fig. 6). The formation of such oval structure is associated with the characteristics of the mixing of metal with different tips of the tool. Adjacent to the core is a complex profile that forms the top of the seam.

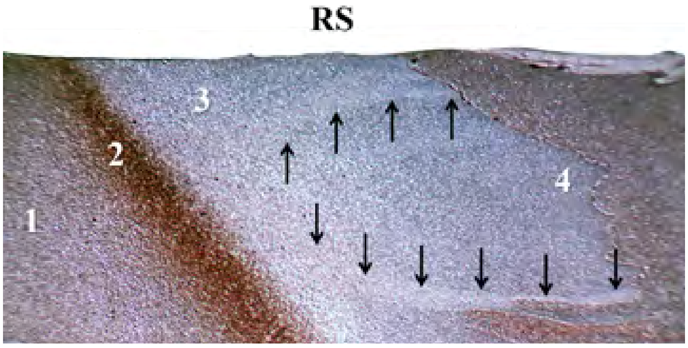

Fig. 6. Formation of oval structure in core of C-type FSW joint

At a result of the samples etching the defects of the joints emerged in the form of local discontinuities and cavities along the line separating the center of the core from its surrounding thermo-mechanical zone. These bands are aluminum oxide are inherent in the surfaces of the materials to be welded, because they were not sufficiently mechanically distributed by the welding tool. This type of defect is typical for FSW and depends on the linear welding speed. That means – an increase of linear welding speed the dispersion of oxides during mechanical mass transfer increases and the defectiveness decreases.

Next typical horizontal defect was showed in S-type joint simple tool with smooth cylindrical probe without a thread and a flat shoulder caused by insufficient mixing of materials is results. The reason for such defect is that the flat surfaces of the tool (during friction) lead to local overheating of the metal to the melting temperature.

Thus, four typical zones are formed in FSW joint: directly to zone 1 – base metal, zone 2 adjoins, where the metal remain undeformed and change only in the heat-affected zone (HAZ); zone 3 where the metal is subjected to significant plastic deformation and heating is the zone of thermomechanical action (TMAZ) and zone 4 is the core where dynamic recrystallization occurs.

The mechanical test of FSW joints shown a principal difference of indentation diagrams for base metal (Fig. 7-a) and typical zones (Fig. 7-b) which confirm altered structural state presence.

The hardness of zone 2 (HAZ) is reduced for all three samples. The maximum hardness values are characteristic of zone 4 – the central part of the core (Fig. 8–10), as well as light oval concentric fragments of the structure of the upper and lower parts of the core (Fig. 8 and 10). The averaged values of the physic-mechanical properties of the FSW joints zones of the three types are follows:

- Zone 1 (base metal) – H = 1.2 GPa, E = 70 GPa;
- Zone 2 (HAZ) – H = 0.5-1.0 GPa, E = 45-57 GPa;
- Zone 3 (TMAZ) – H = 1.0-3.0 GPa, E = 63-103 GPa;
- Zone 4 (core) – H = 2.0-7.0 GPa, E = 80-161 GPa.

Figure 8 shows the welded joint obtained by a C-type tool in which the maximum hardness

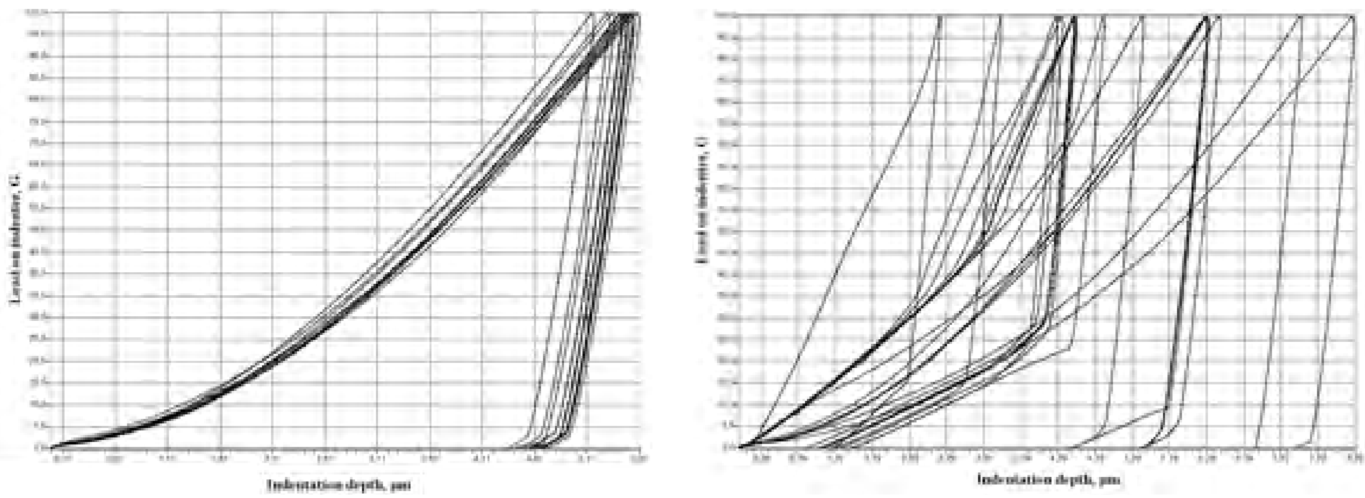

Fig. 7. Indentation diagrams differences for base metal (a) and various zones of the S-type sample (b). The horizontal axis is the depth of penetration of the indenter into the material (μm), the vertical axis is the load on the indenter (G)

value of 7.3 GPa (a light oval fragment of the lower core) and maximum values of E up to 200 GPa and the ratio H/E is up to 0.041. Such values fix the presence of a nano-dispersed multiphase structure formed at the highest degree of deformation. Such structure is also characteristic of the 4th zone of the core of FSW joints: C-type H/E up to 0.041; S-type H/E up to 0.043 in the initial polycrystalline structural state of the base metal H/E=0.017. Such reinforcing during the grinding of grains of the structure is usually associated with a decrease in the density of dislocations and their deceleration.

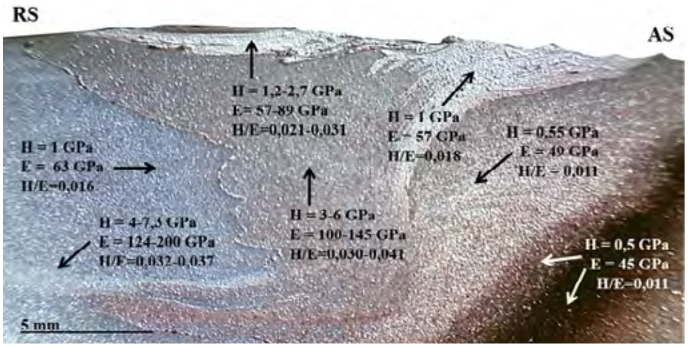

Fig. 8. The distribution of hardness (H), modulus of elasticity (E) and resistance to deformation (H/E) in the microstructure of C-type tool of FSW joint

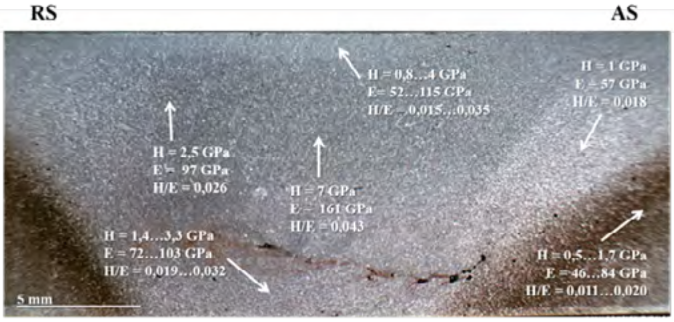

Fig. 9. The distribution of hardness (H), modulus of elasticity (E) and resistance to deformation (H/E) in the microstructure of S-type tool of FSW joint

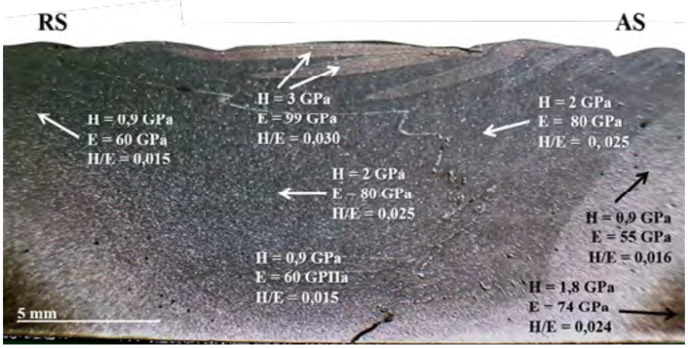

Fig. 10. The distribution of hardness (H), modulus of elasticity (E) and resistance to deformation (H/E) in the microstructure of T-type tool of FSW joint

Thus, if we consider the advantage as the presence of a nano- sized reinforced structure in the FSW joints and the uniformity of its distribution, good dispersion of oxide films and the absence of discontinuities, then the C-type tool is optimal in this study.

During the work was made assume that according to the degree of disperse up to nanodimension of grains the metal structure during twisting deformation, where be possible to determine the number of FSW tool revolutions in one place. If the twisting deformation is considered in the form of a spiral mathematical Fibonacci proportion – 1, 2, 3, 5, 8, 13 ... (Fig. 11-a), where a full turn (unwinding) is a sequence of four values, then in the opposite direction (twisting) the helix, a substantial refinement of the structure will turn out after deformation by a half-turn of 0-1800 (fig. 11-b), and to create a homogeneous nanostructure, a deformation of several turns is required.

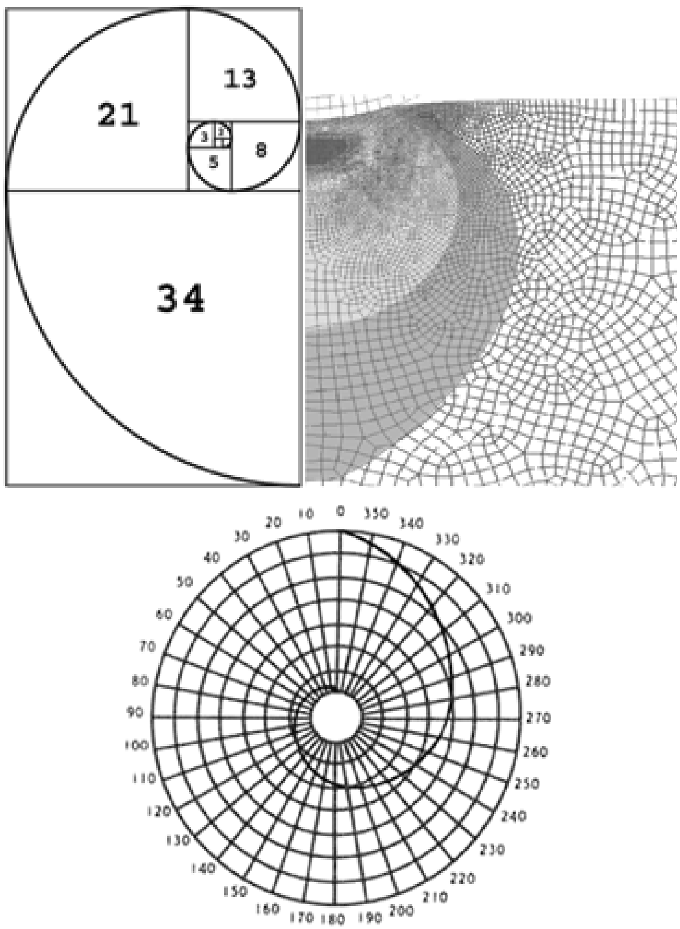

Fig. 11. The Fibonacci spiral as FSW model at changing the large-scale structure fragments (a) and a degree change of segments during twisting (b)

Taking the average grain diameter of the changed nano- structure as 100 nm and the average grain diameter of the base polycrystalline aluminium as 100 000 nm (0.1 mm) they scale ratio is 1:1000. Therefore, the grinding of grain in such inverse proportion will occur at 3–4 revolutions of FSW tool in one place:

- 1 turn – 1597, 987, 610, 377,
- 2 turn – 233, 144, 89, 55,
- 3 turn – 34, 21, 13, 8,
- 4 turn – 5, 3, 2, 1.

This can be controlled technologically – by changing the speed of rotation and/or the linear speed of movement of the tool during welding, but usually the welding equipment has a fixed speed, which limits the control.

FSW is a complex thermo-physical process and the study of metal flow under the tool during stirring is associated with phase transformations in aluminium. Friction between the pin and the plate presented in the model as a surface heat source. Convection and radiation between the surface and the environment remove heat from the plates. The effect of temperature on the properties of the aluminum alloy and, therefore, its shear stress described using the interpolation function [18] (Fig. 12).

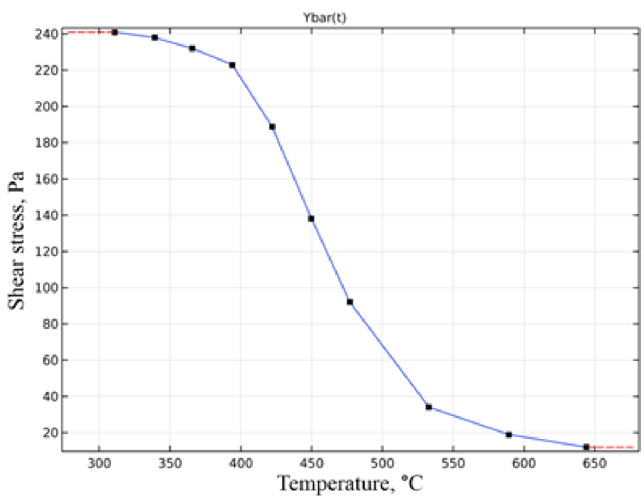

Fig. 12. Interpolation function that determines the relationship between temperature (°C) and shear stress (Pa)

So, the movement of the C-type tool was replaced by the effect of convective heat flux, which moves at the same speed as the FSW instrument. This to simplify the model, making it easier to solve the stationary problem of convection and heat conduction. To simulate these phenomena, heat transfer coefficients have been calculated using empirical values. The temperature (°K) is highest where the aluminium contacts the rotating tool (Fig. 13) and corresponds to the melting point of aluminum. Hot material moves behind the tool and new cold material enters in front of the tool.

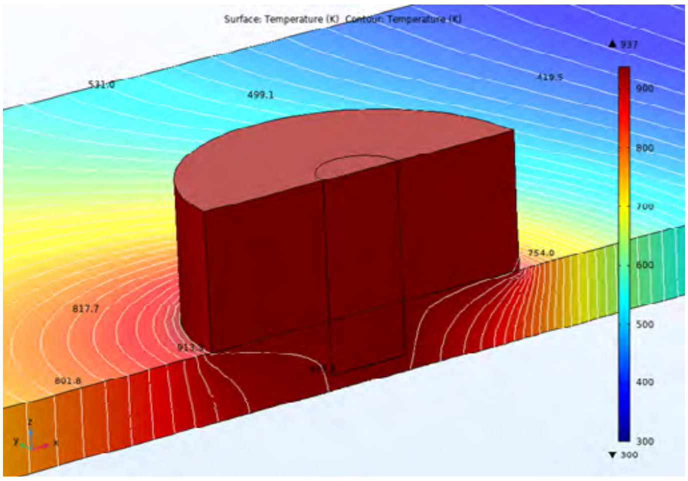

Fig. 13. Heat transfer during FSW using C-type tool (AS right, RS left)

Therefore, the formation of nano-dispersed hardening in FSW welds of aluminum plates of 8 mm thickness at tool rotational speed – 710 rev./min and linear welding speed – 900 mm/min can be obtained using C-type tool after 3–4 rev. in one place.

Conclusion

The physic-mechanical properties of welds EN AW 6082-T6 alloy joints which obtained by friction stir welding using three tools of various geometric shapes were investigated. The hardness decreases in heat-affected zone and hardness increases thermomechanical affected zone for all three samples. The maximum hardness values are characteristic of the central part of core and light oval concentric fragments of the structure in upper and lower parts of the core.

By the presence of a nano-sized reinforced structure in the weld core and the uniformity of its distribution, as well as good dissipation of oxide films and the absence of discontinuities, the FSW tool of the C-type is optimal.

It has been suggested that the formation of a uniform structure in the welds can be obtained at 3–4 rev. of FSW tool on one place.

The model of thermal fields distribution in Al-plate during FSW using a C-type tool visualized the metal's thermal condition when occurs the formation of hardened nano-dispersed weld zones.

References

[1]Thomas W. M., Nicholas E. D., Needham J.C., Murch M. G., Temple-Smith P., Dawes C.J. (1991) Friction stir butt welding. European Patent Specification 06 15 480 B1.

[2] Dawes C. J. (1995) An introduction of friction stir welding and its development. Welding & Metal Fabrication, vol. 63,13–16.

[3] Mishra R. S., Ma Z. Y. (2005) Friction Stir Welding and Processing. Mater. Sci. Eng., 50A, 1–78.

[4] Uday M. B., Ahmad Fauzi M. N., Zuhailawati H., Ismail A. B. (2010) Advances in Friction Welding Process: A Review. Sci. Technol. Weld. Join., 15, 534–558.

[5] Krasnowski K., Sędek P., Łomozik M., Pietras A. (2011) Impact of selected FSW parameters on mechanical properties of 6082-T6 aluminium alloy butt joints. Archives of Metallurgy and Materials, Vol. 56, 4, 965–973.

[6] Threagill P. L., Leonard A. J., Shercliff H. R., Withers P. J. (2009) Friction Stir Welding of Aluminium Alloys. Int. Mater. Rev., 54, 2, 49–93.

[7] Nandan R., DebRoy T., Bhadeshia H.K.D.H. (2008) Recent Advances in Friction-Stir Welding: Process, Weldment Structure and Properties. Prog. Mater Sci., 53, 980–1023.

[8] Krasnowski K., Dymek S. (2013) A comparative analysis of the impact of tool design to fatigue behavior of single-sided and double-sided welded butt joints of EN AW 6082-T6 Alloy. Journal of Materials Engineering and Performance, Vol. 22, 12, 3818–3824.

[9] Krasnowski K. (2014) Fatigue and static properties of friction stir welded aluminium alloy 6082 lap joints using Triflute-type and smooth tool. Archives of Metallurgy and Materials, Vol. 59, 1, 157–162.

[10]Kalemba I., Kopyscianski M., Dymek S. (2010) Investigation of Friction Stir Welded Al-Zn-Mg-Cu Aluminum Alloys. Steel Research International, vol. 81, 9 , 1088–1096.

[11] Mustafa B., Adem K. (2004) The influence of stirrer geometry on bonding and mechanical properties in friction stir welding process. Materials and Design, vol. 25, 343–347.

[12] Standard DIN EN 573 – 3:2009, Aluminium and aluminium alloys. Chemical composition and form of wrought products. Chemical composition and form of products.

[13] Oliver W. C. and Pharr G. M. (1992) An Improved technique for determining the hardness and elastic modulus using load displacement sensing indentation experiments. J. Mater. Res.7, 1564–1583.

[14]Kazuhisa Miyoshi (2002) Surface Characterization Techniques: An Overview NASA/TM-2002-211497, 12–22.

[15] Khokhlova Yu. A., Klochkov I. M., Grinyuk A. A., Khokhlov M. A. (2009) Verification of Young modulus measurement by nanoindenter „Micron-gamma". Journal „Nondestructive control and technical diagnostics", 1, 30–32.

[16]Nano indenters from micro star technologies. Revision 2.3, 9.

[17]Khokhlova Yu. A., Ishchenko D. A., Khokhlov M. A. (2017) Indentation from micro to nano level and examples of study properties the materials of special structure. Journal „Nondestructive control and

technical diagnostics", 1, 30–36.
[18] M. Song, R. Kovacevic. Thermal modeling of friction stir welding in a moving coordinate system and its validation. Int'l J. of Machine Tools & Manufacture, vol. 43, 2003, pp. 605–615.