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Friction Stir Welding of Aluminium Using Probes of Various Geometry

Abstract: The article presents tests related to mechanisms accompanying the formation of friction welds made using variously shaped probes for aluminium sheets. In addition, the article discusses the effect of applied FSW technology parameters on the quality, form and repeatability joints. The tests included the microscopic analysis of structures formed when making aluminium joints using a rotating probe.

Keywords: friction welding, FSW, friction stir welding

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Introduction

Recent decades have seen the growing popularity of a joining method where the weld is obtained using a rotating probe. The above-named method enables the joining of dissimilar materials, the modification of surface layers as well as the fabrication of multilayered structures. As the process increases fatigue strength and corrosion resistance, it has been enjoying growing popularity in industrial applications entailing the dynamic development of the method. The friction stir welding method (FSW) is a joining process, where the formation of a joint results from the plasticisation of materials induced by friction heat emitted by a tool containing a special probe. Friction is triggered by the rotation of the probe in the joint area as well as by the travel of the probe along the joint line. Importantly, the FSW process does not involve the melting of the material. The FSW method is used to join poorly weldable materials including steels, alloys of aluminium, titanium, copper, alloys of nickel, zirconium, etc. Tests concerning the hardness of the base material before and after being subjected to the FSW process revealed that, depending on their thickness, the relative strength of joints is restricted within the range of 75% to 96% [1]. Most (properly made) welds in aluminium are characterised by hardness constituting 80% of the base material hardness. Slight differences in strength indicate the high applicability and usefulness of the FSW method. In addition, fatigue-related tests and tests connected with ultimate loads [2] of riveted joints as well as service life-related tests revealed that the above-named properties can be significantly improved using the FSW technology. The FSW method is effective, improves the rigidity of joints and significantly reduces the formation of potential sources of fatigue cracks.

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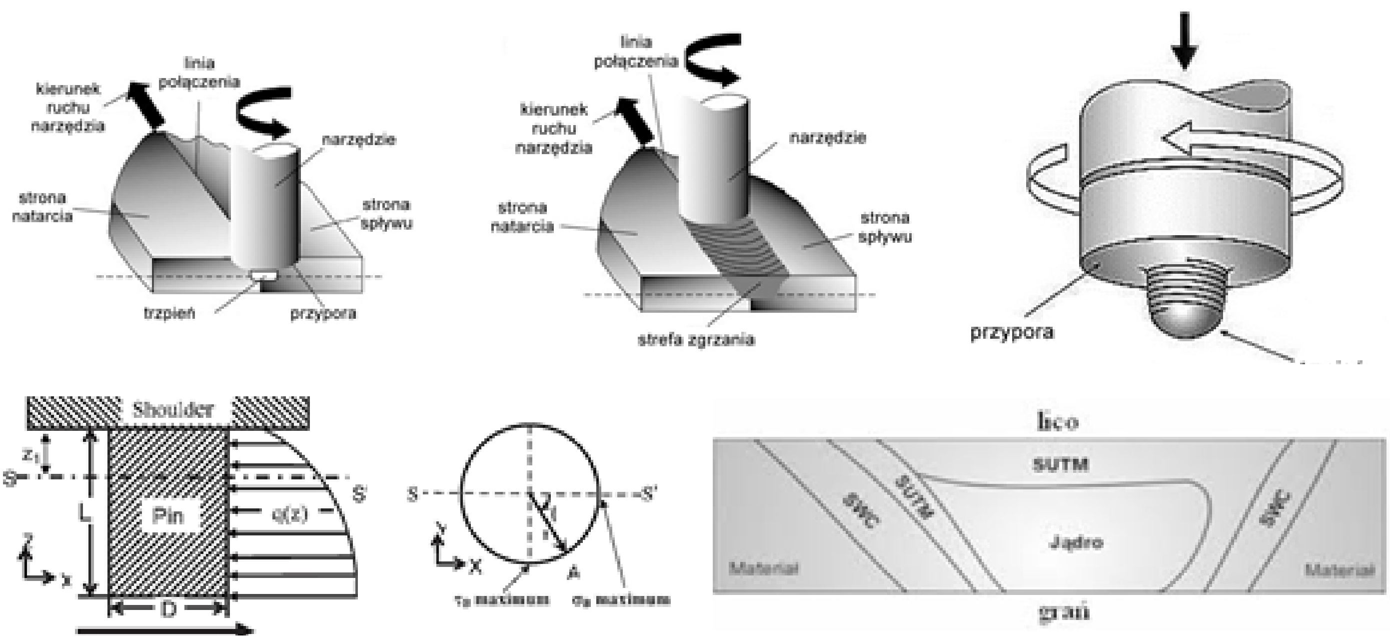

Fig. 1. (a, b) joining method [5], (c) roller with a probe used in the FSW method [3], (d) distribution of forces on a cylindrical probe with normal stresses (σ_B) shear stresses (τ_B) presented in cross-section [9], (e) typical cross-section of a joint. TPZ – thermomechanically processed zone, HAZ – heat affected zone [5]

FSW technology

The FSW method (Fig. 1) enables the making of a joint (along the linear alignment of elements to be joined) by the stirring of the material (of elements) with a probe rotating at a specific rotation rate and moving at a previously adjusted travel rate. A typical rate of rotation is restricted within the range of 150 rpm to 1600 rpm, whereas a typical travel rate exceeds 25 mm/min.

An important aspect of the FSW technology is the shape of probes used for the joining of materials. It is assumed that the height of the probe is equal to the thickness of the material subjected to butt welding. As regards the hardening of the surface layer, the probe is modified in relation to a material subjected to processing. Figure 2 presents the most popular joining methods involving the use of the rotating probe.

An optimum solution involves an appropriate probe design. The shapes of the most popular probes used in the FSW technology are presented in Figure 3.

An inseparable phenomenon accompanying the application of the FSW method is the "zigzag defect", significantly affecting the service live of a material subjected to joining (if compared with the service life of the base material). The aforementioned issue is discussed more exten-sively in publication [10, 11].

Tests [11] revealed that, with time, stresses in the area of the direct stirring of the material decrease whereas stresses in the heat affected zone increase significantly. To reduce the above-named effect it is necessary to adjust the optimum rate of rotation and the travel rate of the tool. Authors [12, 13] state that, in relation to aluminium series 2xx, 6xx and 7xx, the rate of rotation should amount to 1300 rpm, whereas the travel rate should amount to 60 mm/min, providing optimum hardness in the stirring zone. Hardness in the intermediate zones is similar to that of the weld nugget and provides

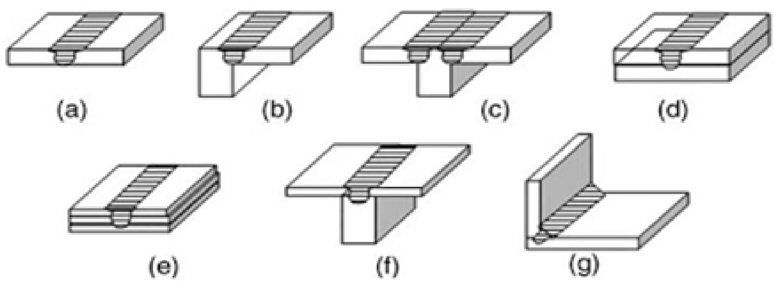

Fig. 2. FSW joint configurations (a) square butt joint, (b) edge joint, (c) T butt joint, (d) lap joint, (e) multiple lap joint, (f) T lap joint and (g) fillet joint [6]

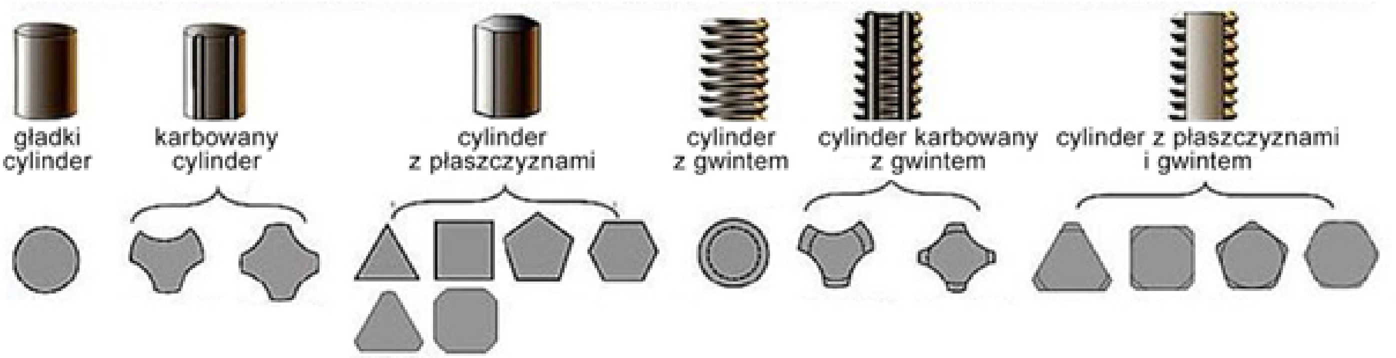

Fig. 3. Most popular probes used in the FSW technology [6]

stress equilibrium. In cases of lower rotation rates, the hardness of the weld nugget zone is significantly higher than that of the base material. As a result, the heat affected zone is characterised by significantly lower hardness, which consider-ably weakens the material. Increasing the rate of rotation up to 1500 rpm is followed by a significant decrease in hardness and the deterioration of material properties. The foregoing is manifested by the cracking of the material along the heat affected zone during the test bending of joined sheets (Fig. 4). Depending on the design of a given tool, maximum forces affecting the tool are restricted within the range of 4 kN to 14 kN. Usually, the aforesaid forces do not exceed 6 kN. [14]

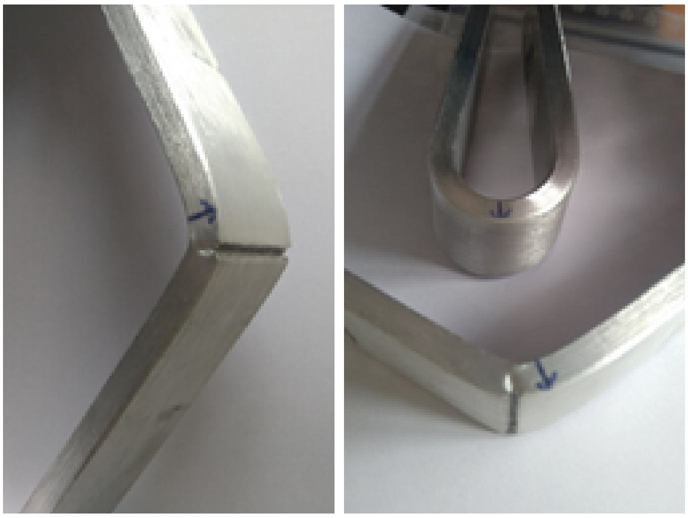

Fig. 4. a) Improper FSW parameters (arrow shows the joint area of the sheets; crack along the HAZ); b) properly performed test [4]; bend test was performed in relation to the same parameters

The tests of the probes [15] revealed the varied wear of the side surface of the probe. The greatest radial wear was observed at a height restricted within the range of 0.2 mm to 0.4 mm and at a height restricted within the range of 1.0 mm to 1.2 mm. In turn, the smallest wear was observed at a height of 0.8 mm as well as on the front surface of the tool. The long-lasting operation of the tool (Fig. 5) is accompanied by intensified wear across the entire work surface, with exception for the front surface of the probe (where decreased wear could be observed) [15].

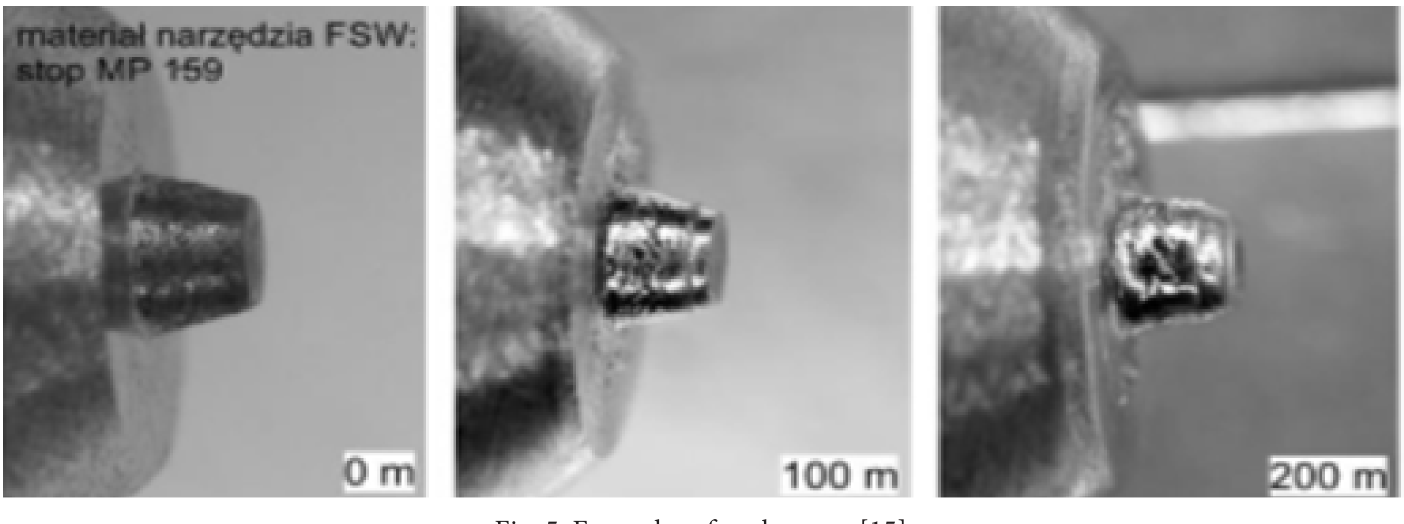

Fig. 5. Examples of probe wear [15]

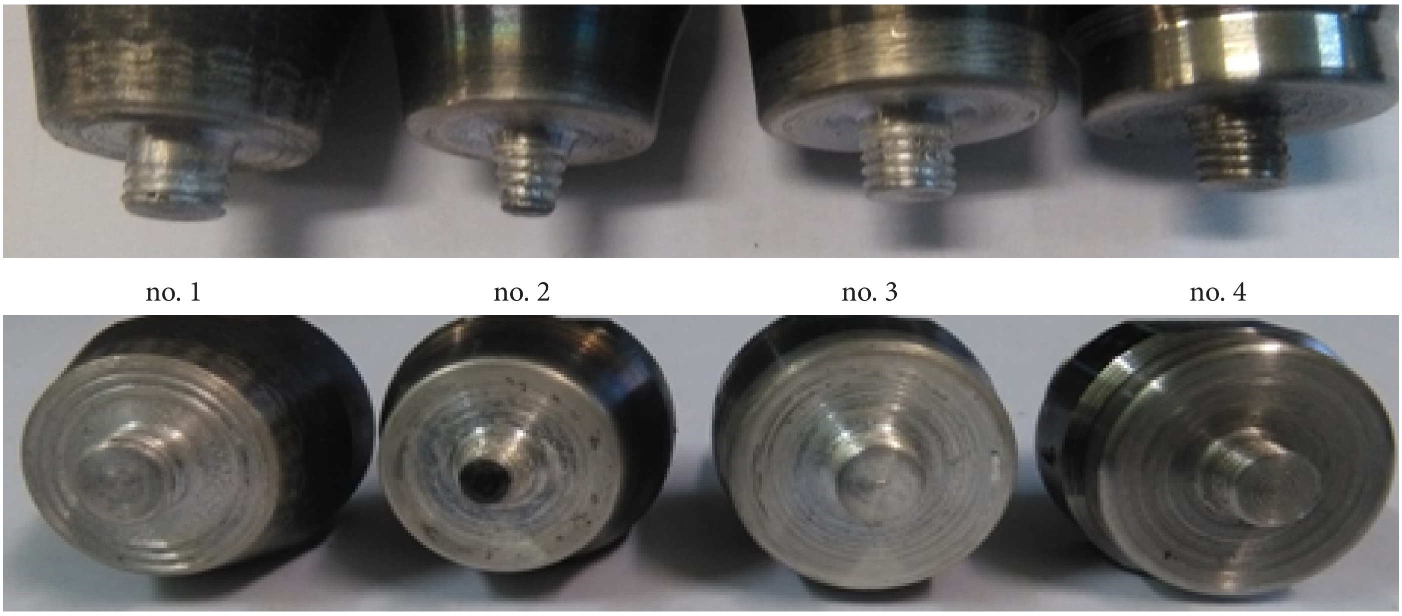

Fig. 6. Side and front view of FSW probes [4]:
1 – cylindrical probe with the right-hand thread Φ = 7 mm and streaks on the shoulder 18 mm;
2 – conical probe with the left-hand thread; size at the shoulder: 6.4 mm, size at the end: 4 mm, smooth shoulder; .
3 – cylindrical probe with the right-hand thread: 6.8 mm, smooth shoulder: 22.5 mm;
4 – cylindrical probe with the left-hand thread: 6.8 mm, smooth shoulder: 22.5 mm

The tool wear manifested by changes in its geometry and triggered by both the mechanical and thermal load affecting the tool work surface results from mechanical abrasion, plastic deformation, oxidation, adhesion, spalling etc. The wear can be prevented by appropriately adjusted process parameters, appropriately selected tool material and as well as the use of antiadhesive coatings preventing the tool wear. The excessive wear manifested by changes in the shape of the tool increases the probability of the formation of weld imperfections. Leftovers of the tool material or of the coating in the joint material adversely affect joint properties and, for this reason are unacceptable. In addition, the above-named leftovers may favour the formation of local corrosion centres [16–21].

Individual tests

The tests concerning the FSW process involved the use of a 6P 13K milling machine [4]. The welding process was performed using the probes presented in Fig. 6. During the process, the probes were inclined at an angle restricted within the range of 1°to 3°.

Unlike fusion welding, the friction welding process does not require the preliminary preparation of materials to be joined. An extremely important aspect of the FSW method is the appropriately applied pressure of sheets so that, during the FSW process, the material is properly obtained and stirred without imperfections (formed as a result of improperly adjusted process parameters (Fig. 7). Properly made joints are presented in Figure 8. The research work involved the making of a 3D map of rings formed during penetration through the material. The map presents changes in the geometry of space after the FSW process in relation to aluminium 5754 (Fig. 9–11). The joints were subjected to microscopic observations performed using an Olympus IX 70 microscope at a magnification of 50x, 100x and 200x. The structure of the weld, HAZ, thermomechanically processed zone and of the weld nugget are presented in Figure 12.

The metallographic specimens were included and subjected to hardness measurements (Vickers hardness test) involving all areas of the joint. The tests were made using a microhardness tester (Leco) under a load of 0.98 N. Averaged test results are presented in Table 1.

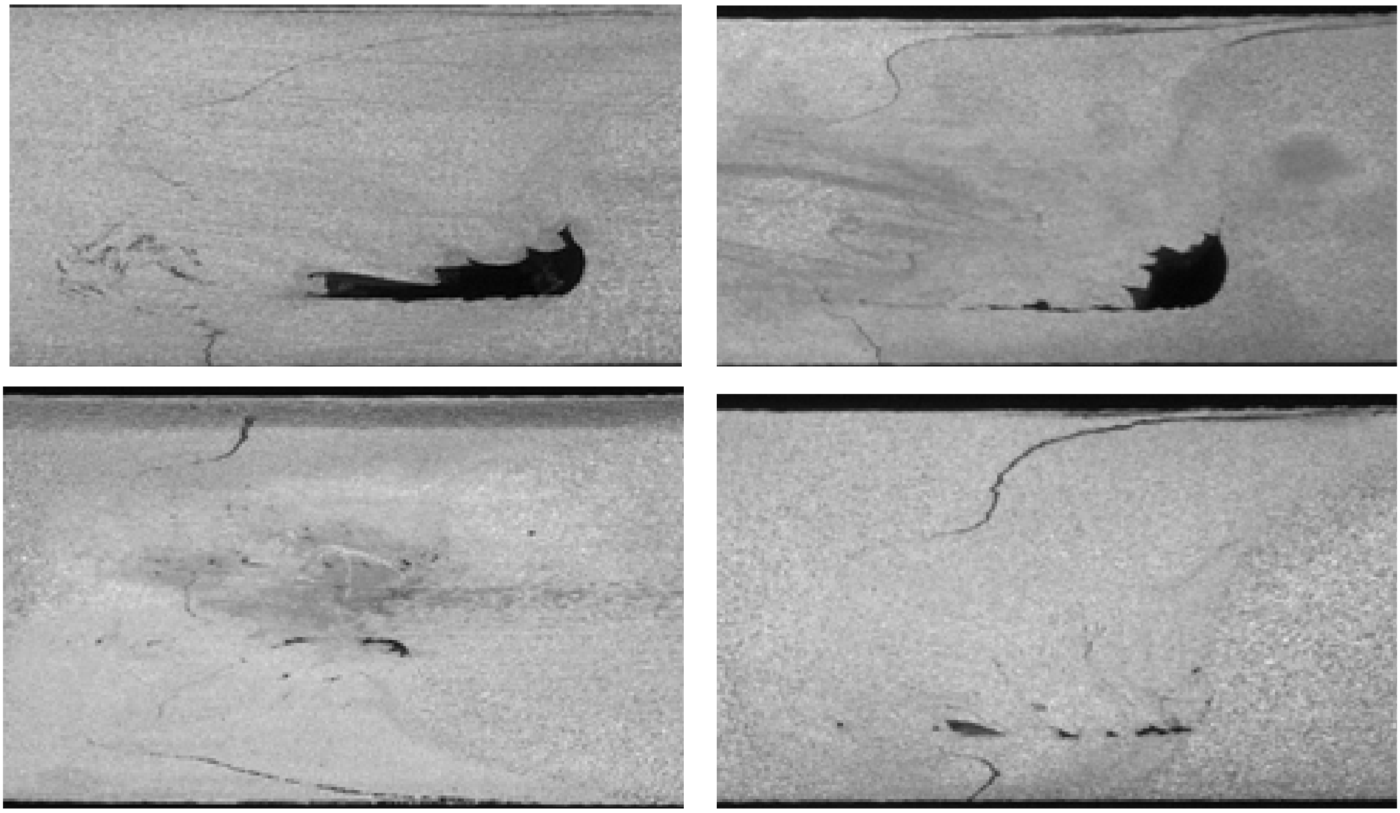

Fig. 7. Imperfections present in aluminium 5754 as a result of the FSW process; visible incomplete stirring resulting from improperly adjusted process parameters; a) rotation rate of 400 rpm, travel rate of 250 mm/min, b) rotation rate of 400 rpm, travel rate of 200 mm/min, c) rotation rate of 400 rpm, travel rate of 200 mm/min [4]

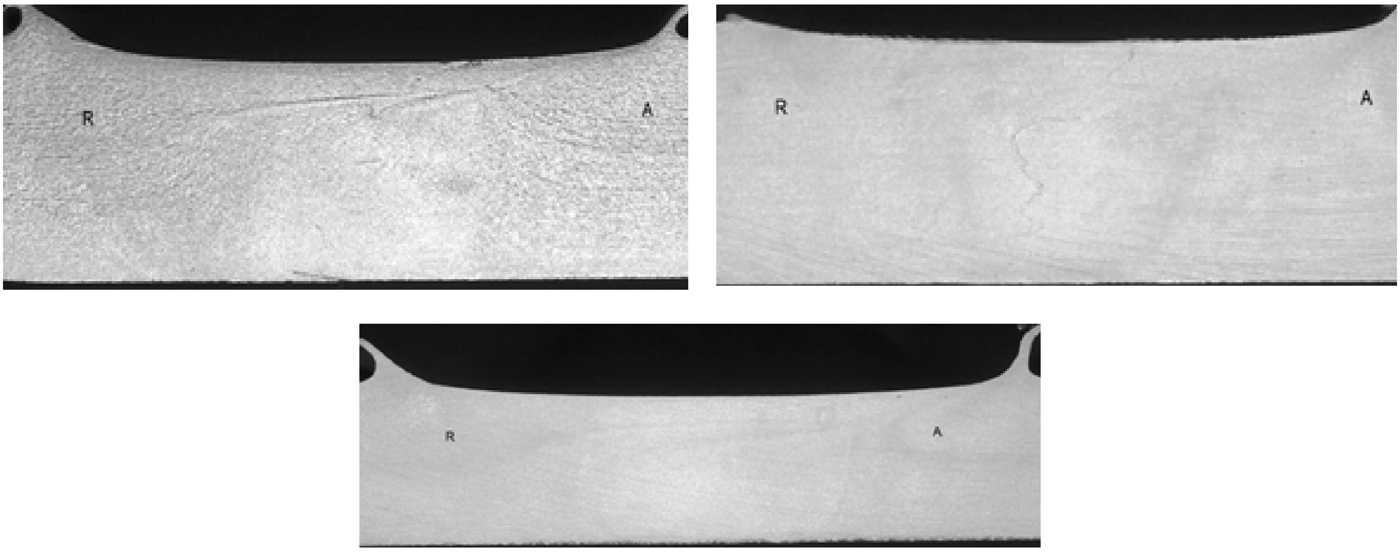

Fig. 8. Welds made using properly adjusted parameters:
a) 500 rpm, travel rate of 160 mm/min, probe inclined at an angle of 2°,
b) 400 rpm, travel rate of 160 mm/min, probe inclined at an angle of 3°,
c) 400 rpm, travel rate of 125 mm/min, probe inclined at an angle of 3°

Table 1. Microhardness measurement results (HV) of FSW zones in aluminium 5754

Specimen	Base material	HAZ	TPZ	Weld nugget
Right-hand cylindrical probe	55 HV	72	85	91
Left-hand cylindrical probe	55 HV	79	84	93
Right-hand conical probe	55HV	68	78	88

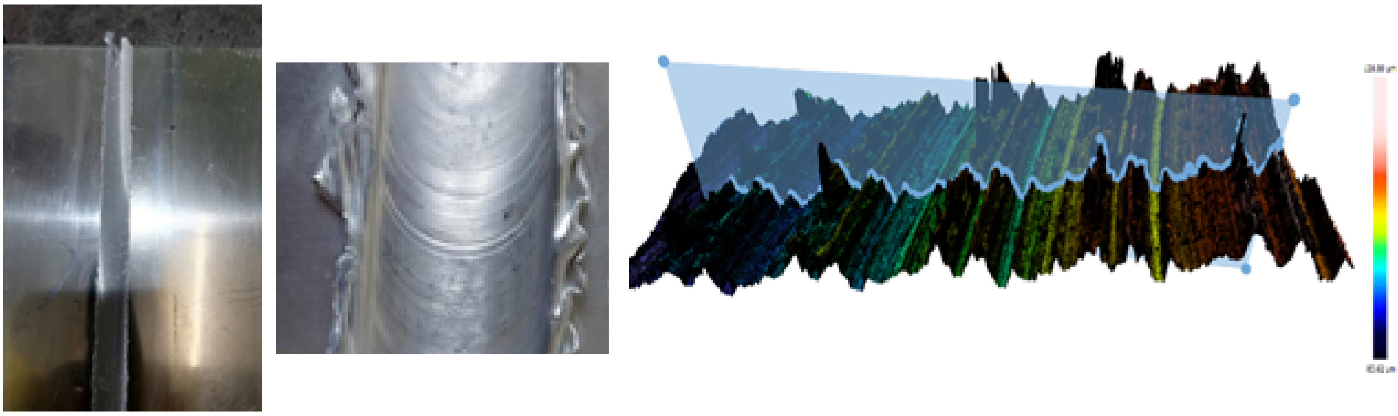

Fig. 9. Specimen 1; a) probe with the left-hand thread; parameters: rotation rate of 400 rpm, travel rate of 160 mm/min, inclination of 2° b) 3D image of the distribution of irregularities after a run of the tool

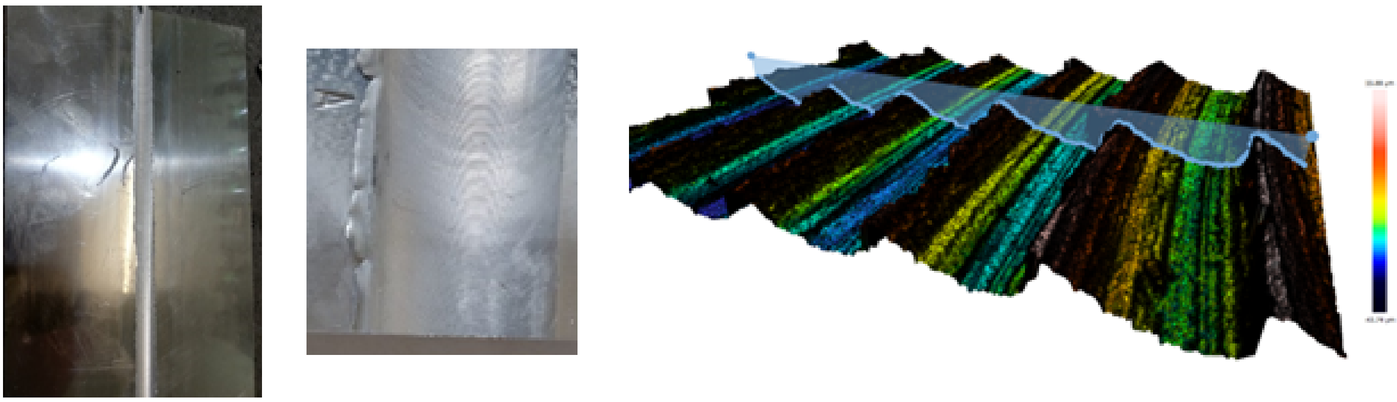

Fig. 10. Specimen 2; a) probe with the left-hand thread; parameters: rotation rate of 400 rpm, travel rate of 160 mm/min, inclination of 3°, b) 3D image of the distribution of irregularities after a run of the tool

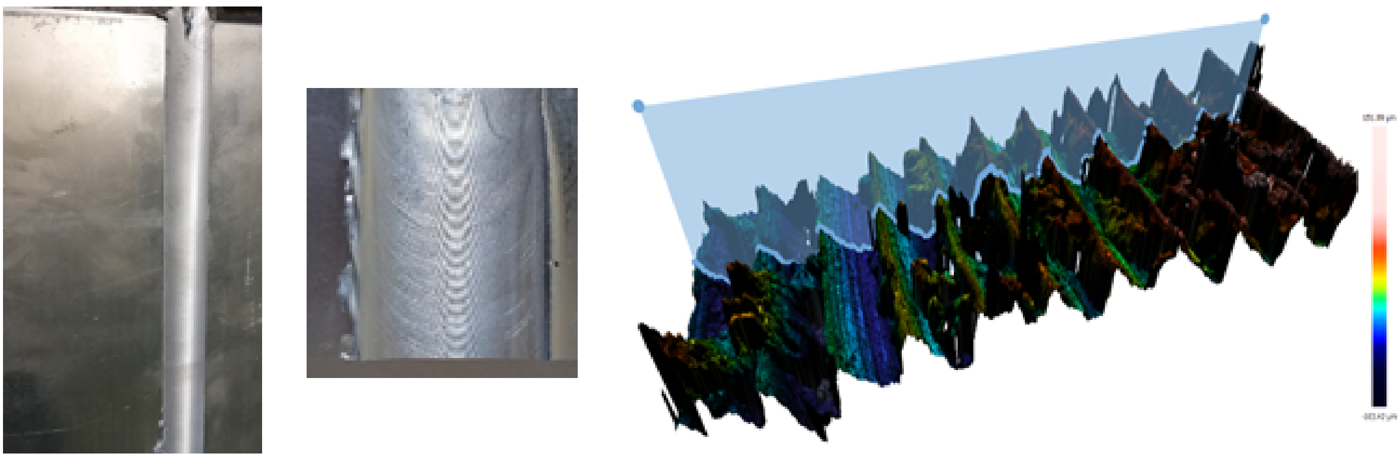

Fig. 11. Specimen 3; a) conical probe with the left-hand thread; parameters: rotation rate of 500 rpm, travel rate of 160 mm/min, inclination of 3°, b) 3D image of the distribution of irregularities after a run of the tool

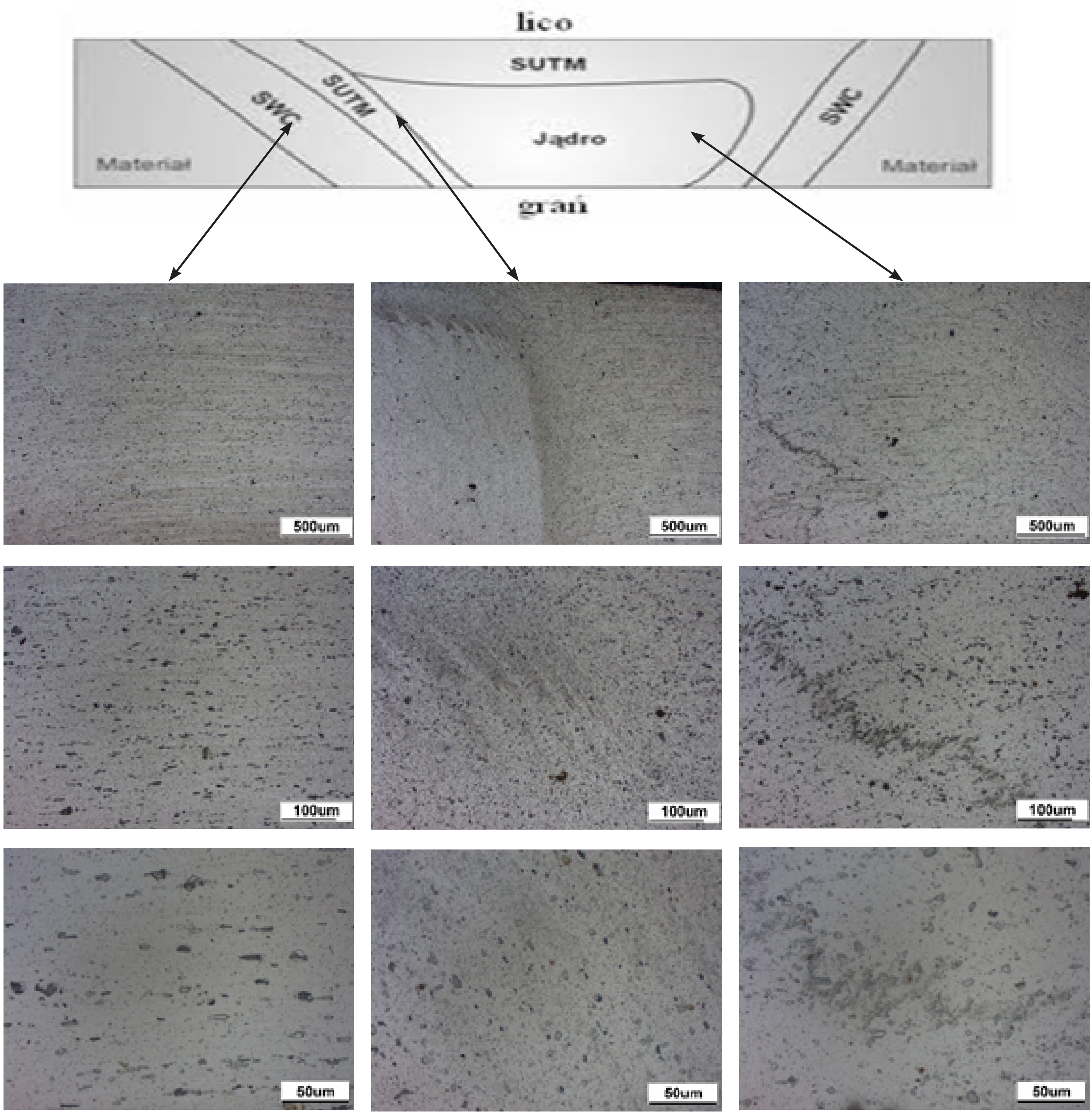

Fig. 12. Structure of the FSW joint in aluminium 5754

Summary

The above-presented tests revealed the correlation between the quality of joints and process parameters (Fig. 7–8) as well as types of probes (Fig. 9–11). The joints obtained in the tests contained a few characteristic areas, i.e. the heat affected zone (HAZ), the thermomechanically processed zone and the weld nugget. The weld nugget contained the so-called "zigzag defect". In the macroscale the aforesaid defect resembled a crack, yet microscopic observations revealed that the "crack" was a zone containing oxides formed during the stirring of the material. The above-named zone took various shapes depending on a probe and its rate of rotation. The hardness tests revealed that the zone was detrimental to the service life of the material; the weld nugget was characterised by a locally significant increase in hardness, particularly in the "zigzag defect" zone.

References

[1] Mishra R. S.: Friction Stir Processing Technologies. Advanced Materials & Processes, 2003, vol. 161, no. 10, October 2003, pp. 43–46.

[2] Schmidt H. J., Schmidt-Brandecker B.: Advanced materials and manufacturing technologies for aircraft application. 2nd Int. Conf. Materials and component performance under variable amplitude loading. Darmstadt, 2009, pp. 67–87.

[3] Reynolds A. P.: Effect of Tool Pin Features and Geometries on Quality of Weld During Friction Stir Welding. W: Friction stir welding and processing VII. Springer, Cham, 2013, pp. 163–172.

[4] Materials, equipment and machinery used in FSW tests were made available by Spółka AS z.o.o. koman. (registered partnership) in Opole

[5] https://en.wikipedia.org/wiki/File:Anand-FSW-Figure1-B.jpg.

[6] Burek R., Wydrzyński D., Sęp. J., Więckowski W.: The Effect of Tool Wear on the Quali-ty of Lap Joints Between 7075 T6 Aluminum Alloy Sheet Metal Created with the FSW Method. Eksploatacja i Niezawodność – Maintenance and Reliability, 2018; vol. 20 no. 1: 100106.

[7] Fall A., Fesharaki M. H., Khodabandeh A. R., Jahazi M.: Tool Wear Characteristics and Effect on Microstructure in Ti-6Al-4V Friction Stir Welded Joints. Metals, 2016, vol. 6, no. 11: 275, pp. 1–12.

[8] Sato Y., Urata M., Kokawa H.: Parameters controlling microstructure and hardness during friction-stir welding of precipitation-hardenable aluminum alloy 6063. Metallurgical and Materials Transactions A, (March) 2002, 33A, pp. 625–632.

[9] Arora A., Mehta M., De A., DebRoy T.: Load bearing capacity of tool pin during friction stir welding. The International Journal of Advanced Manufacturing Technology, 2012, vol. 61, no. 9–12, pp. 911–920.

[10] Di S. et al.: Comparative study on fatigue properties between AA2024-T4 friction stir welds and base materials. Materials Science and Engineering: A, 2006, no. 435–436, pp. 389–395.

[11] Linton V. M., Ripley M .I.: Influence of time on residual stresses in friction stir welds in agehardenable 7xxx aluminium alloys. Acta Materialia, 2008, vol. 56, no. 16, pp. 4319–4327.

[12] Christner B.: Enabling technology for an aircraft alternative. Mechanical Engineering Magazine, 2003, vol. 125, no. 3, D14.

[13] Davis D. J., McArthur J. C.: NASA Ares I Crew Launch Vehicle Upper Stage Overview. 44th AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit, American Institute of Aeronautics and Astronautics – AIAA, Connecticut, CT, USA, July 21–23, 2008.

[14] Hattingh D.G. et al.: Characterization of the influences of FSW tool geometry on welding forces and weld tensile strength using an instrumented tool. Journal of Materials Processing Technology, 2008, vol. 203, no. 1–3, pp. 46–57.

[15] Więckowski W., Burek R., Lacki P., Łogin W.: Analiza procesu zużycia narzędzi wykonanych ze stali 1.2344 oraz stopu MP159 w procesie zgrzewania tarciowego z przemieszaniem (FSW) blach ze stopu Aluminium 7075 T6, research project DTR/B

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The Cutting of Steels Using Various Methods

Abstract: The article describes tests of steel subjected to cutting with laser, plasma and abrasive waterjet. The research discussed in the article also involved microstructure observation and changes in hardness after cutting are as well as the assessment of surface quality based on measurements of surface parameters.

Keywords: laser, plasma, abrasive waterjet, surface quality

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Introduction

The cutting of materials tends to be the first operation when making structural elements. The primary issue concerning the cutting of materials is the condition of the surface layer, affecting the properties of a given product, primarily its hardness, brittleness and corrosion resistance. In addition, the surface condition may necessitate the application of finishing treatment.

Technologically advanced cutting techniques make it possible to obtain products in finished forms, where the selection of a cutting method depends on quality-related requirements as well as technical and financial possibilities of the producer [1]. Primary criteria taken into consideration when selecting a given cutting technology include the type of material and its thickness, the accuracy and time of cutting, the quality of a surface to be cut, dimensional tolerances, the shape of elements to be cut out and the cost of cutting [2]. In cases of processes which might result in local hardening, before selecting a given cutting method it is necessary to verify its usability in PN-EN 1090-2 [1]. The above-named standard specifies the maximum surface hardness for structural steels. Depending on types of products and steel grades, the maximum hardness amounts to 380 HV or 450 HV [3].

In industrial practice, the most common cutting methods involve the use of oxygen, plasma, laser or waterjet [4]. Presently, plasma cutting is the leading method, which can probably be ascribed to high efficiency, good surface quality after cutting, the possibility of cutting thick materials (up to 150 mm) and favourable economic indicators [5]. The method can be used for cutting nearly all current conducting materials, i.e. steel, cast iron, aluminium and copper [4]. In addition, the use of special heads with independent arc extends the method application range and enables the cutting of non-metallic materials (plastics, rubber or glass) [1].

Laser cutting is characterised by the significant degree of automation as well as high efficiency and flexibility (e.g. when changing the scope of production). Another advantage of the technology is the narrow HAZ, cutting accuracy, lower hardening than that resulting from plasma cutting, a high cutting rate and the high quality of surface of the cutting process [6]. The laser cutting method can be

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