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K. KRASNOWSKI*, P. SĘDEK*, M. ŁOMOZIK*, A. PIETRAS*

IMPACT OF SELECTED FSW PROCESS PARAMETERS ON MECHANICAL PROPERTIES OF 6082-T6 ALUMINIUM ALLOY BUTT JOINTS

WPŁYW WYBRANYCH PARAMETRÓW PROCESU ZGRZEWNIA METODĄ FSW NA WŁAŚCIWOŚCI MECHANICZNE DOCZOŁOWYCH ZŁĄCZY STOPU ALUMINIUM 6082

In the friction stir welding (FSW) process a rotating and travelling tool equipped with a specially designed probe is slowly plunged into joined materials, plasticizes and stirs them thus forming a joint. Various geometric shapes of stirring tools make the motion of plasticized material very complex, which, in turn, translates to the structure and mechanical properties of joints. The article presents the results of tests focused on the impact of selected FSW process parameters on the mechanical properties of butt welded joints made of 6082 aluminium alloy. The tests were performed at various linear welding speeds, using single- and double-sided test joints welded with three types of stirring tools, differing in probe and shoulder geometry. The article reveals the results of mechanical and fatigue tests of the FSW joints.

Keywords: mechanical properties of FSW joints, tensile strength of FSW joints, fatigue strength of FSW joints, FSW process parameters

W procesie zgrzewania FSW obracające i przesuwające się narzędzie z odpowiednio zaprojektowanym trzpieniem zagłębia się w łączone materiały, uplastycznia je oraz miesza ze sobą przez co powstaje złącze. Różne kształty geometryczne narzędzi mieszających sprawiają, że ruch uplastycznionego materiału jest bardzo złożony. Przekłada się to na budowę strukturalną złączy i ich właściwości mechaniczne. W artykule przedstawiono wyniki badań wpływu wybranych parametrów procesu zgrzewania metodą FSW na właściwości mechaniczne doczołowych złączy zgrzewanych ze stopu aluminium 6082. Badania prowadzono na złączach próbnych zgrzewanych jednostronnie oraz dwustronnie przy użyciu trzech typów narzędzi mieszających, różniących się geometrią trzpienia i wieńca opory, oraz przy różnych prędkościach liniowych zgrzewania. Przedstawiono wyniki badań mechanicznych oraz badań zmęczeniowych złączy zgrzewanych metodą FSW.

1. Introduction

In numerous industrial applications steel is increasingly replaced by non-ferrous, mostly aluminium alloys. Some of these materials combine low weight with high strength, comparable to that of structural steels. The process of joining such materials sometimes proves very problematic. No structural transformations in the solid state along with good heat and electric conductivity cause problems related to welding and resistance welding of aluminium alloys [1]. A solid state joining method known as Friction Stir Welding (FSW) i.e. friction welding with stirring of weld metal (Fig. 1) makes it possible to join many metals which used to be either difficult or even impossible to weld. Although the FSW method can be used for various materials like magnesium and its alloys, copper and its alloys, titanium, zinc or even steel [2], its predominant industrial area of application lies in joining aluminium alloys. The method is applied in the shipbuilding industry for producing ship hulls, catwalks, masts, floorboards etc. Other industries applying of FSW include aviation (e.g. welding of wings, fuselages and fuel tanks), railways (e.g. joining elements of cars and floorboards), transportation (e.g. welding car bodies [3], fuel tanks, bicycle and motorcycle frames) and construction (e.g. joining light bridges, pipelines, window frames, heat exchangers, pipes etc.). The basic types of joints possible to obtain through FSW include butt, overlap and tee joints. A rotating tool equipped with a specially designed probe and shoulder is plunged between edges of elements to be joined and moved along the welding line. Heat necessary to plasticize the material is generated by the friction between the tool and joined materials. The heat obtained in this way plas-

* INSTITUTE OF WELDING, 44-100 GLIWICE, 16-18 BŁ. CZESŁAWA STREET, POLAND

ticizes the material around the probe and its rotational and translational motion cause the mixing of joined materials. As tools may take various geometric shapes, the motion of plasticized material may be complicated. During the FSW process, the material is subject to significant plastic deformations at elevated temperature (lower than the melting point of the material to be joined) which, consequently, leads to the refinement of grains, which is advantageous from joint strength point of view. Fatigue tests carried out by the authors [4] proved the joints welded by means of the FSW method to have significantly higher fatigue strength than that of MIG- or laser-welded joints.

The basic technological parameters of the FSW process include:

– rotational speed of the tool,

– linear welding speed,

– tool inclination angle in relation to the surface of welded elements,

– type of tool and its dimensions (probe diameter, shoulder diameter) [5].

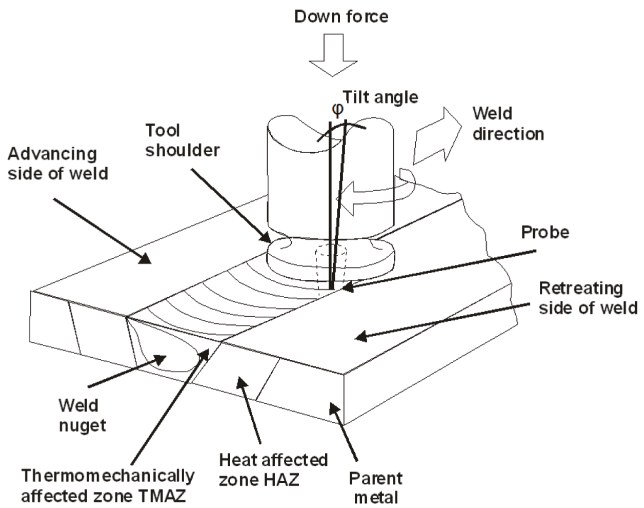

Fig. 1. Principle of FSW process [4]

The proper selection of process parameters makes it possible to obtain joints of appropriate internal structure (without voids and discontinuities) characterised by a very convenient, from strength point of view, fine-grained microstructure. An important element decisive for the proper quality of joints obtained through FSW is the geometry of the probe, playing a key role in the local heating and relocation of stirred materials. Apart from the probe, another important element of the FSW tool is the shoulder, whose main tasks include the generation of heat through the friction between the shoulder and welded materials, transfer of pressure and generation of strains in the weld face area.

The tests focused on the impact of the shape and geometry of the tool on the static and fatigue strength of butt welded joints.

2. Material investigated

The chemical composition of investigated alloy EN-AW 6082 [6] is presented in Table 1.

TABLE 1

Chemical composition of investigated alloy EN-AW 6082

Grade of aluminium alloy	**Si** %	**Fe** %	**Cu** %	**Mn** %	**Mg** %	**Cr** %	**Zn** %	**Ti** %	**Al** %
6082	0.7-1.3	0.5	0.1	0.4-1.0	0.6-1.2	0.2	0.2	0.1	rest

3. Production of test joints and testing methodology

The tests involved production of 8 mm-thick single-side welded butt joints and that of 10 mm-thick double-side welded butt joints (Fig. 2). The joints were produced at three different linear welding speeds of 224, 560 and 900 mm/min and at a constant rotational speed of the tool of 710 rev/min. The direction of tool rotation was clockwise and its angle of inclination in relation to the joined elements was 1.5°.

The joints were produced by means of three tools designated as T1, T2 and T3, where:

- T1 – a conventional tool consisting of cylindrical probe with a thread, of 10 mm diameter and a shoulder with a grooved spiral of 33 mm diameter (Fig. 3a),
- T2 – a Triflute-type tool consisting of cylindrical probe with a thread and three flutes, of 10 mm diameter and a shoulder with a grooved spiral of 33 mm diameter (Fig. 3b),
- T3 – a cylindrical tool consisting of a smooth probe without a thread of 10 mm diameter and a smooth shoulder without a grooved spiral, of 33 mm diameter (Fig. 3c).

The length of the stirring probes in the tools varied for single-side and double-side welded joints and were 7.8 mm and 6.0 mm respectively. The single-side welded joints were produced with T1, T2 and T3 tools, whereas the double-side welded joints were made only with T1 and T2 tools.

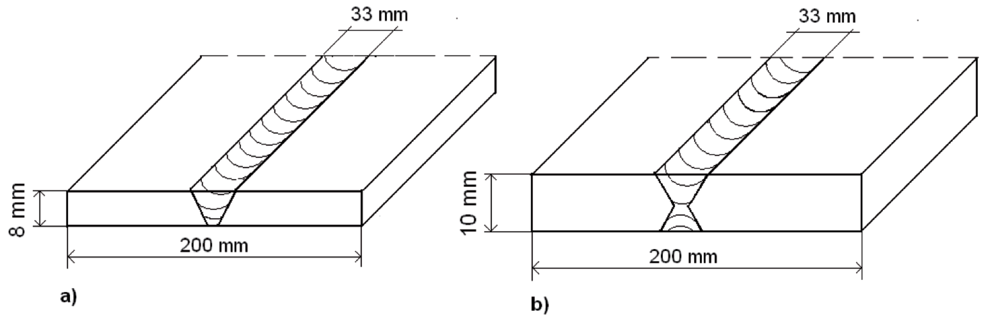

Fig. 2. Sketch of FSW test joints; a) single-side welded joints; b) double-side welded joints

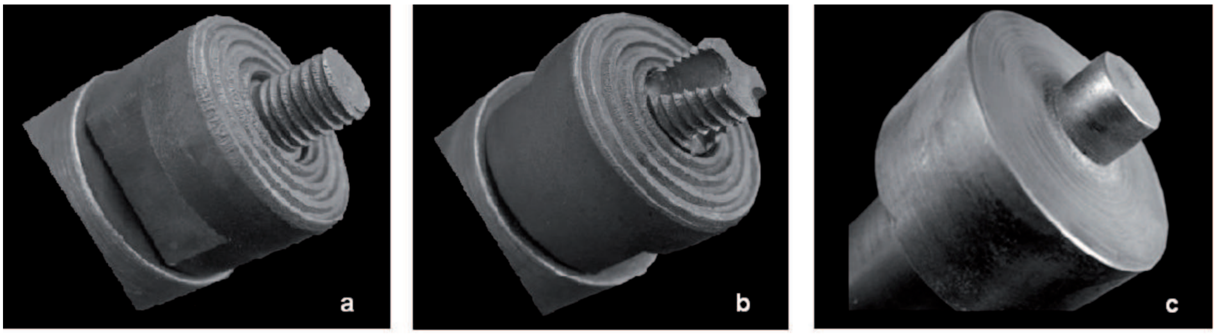

Fig. 3. Tools used in FSW of butt welds; a) T1, b) T2, c) T3

Metallographic specimens for macroscopic examination were prepared according to PN-EN 1321:2000 standard [7]. The tool rotational speed was constant and amounted to 710 [rev/min]. The macrostructure of the joints was revealed through etching with Keller's etchant.

A static tensile test of joints was conducted with flat specimens on INSTRON 4210 testing machine, pursuant to PN-EN 895:1997 standard [8]. The test was performed in order to determine the FSW process parameters ensuring the obtaining of joints characterised by the highest tensile strength and offering the most economical welding process as regards the linear welding speed. Each test run required the use of 3 specimens.

The fatigue tests were conducted with an MTS 810 fatigue-testing machine according to guidelines contained in a document of the International Institute of Welding [9]. The each test run of specimens were conducted on several stress levels $\Delta\sigma$ with a constant stress ratio R=0,2 (minimum to maximum stress ratio) and load change frequency of 20 Hz until the test specimen failure [11]. The shape and geometric dimensions of the specimens used in the fatigue test are presented in Figure 4. The number of specimens used in each test run was between 10 and 15. The single-side welded joints subject to the fatigue tests were those produced with T1, T2 and T3 tools. The joints were tested in two different surface preparation conditions i.e. with characteristic post-weld marks left by the rotating and travelling tool and with mechanically removed post-weld marks. In the aforesaid manner it was possible to assess the impact of surface preparation quality on the fatigue strength of FSW joints. The double-side welded joints subject to the fatigue tests were those produced with T1 and T2 tools; in case of these joints, post-weld marks (forming a geometric notch) were removed.

The joints selected for fatigue tests were those produced at a linear welding speed of 900 mm/min and rotational speed of 710 rev/min. The aforesaid parameters ensured the most economical welding process (from welding speed point of view) and the joints were characterised by very high tensile strength and proper internal structure; they revealed metallic continuity in the whole of cross-section, as was the case with the joints produced at lower linear welding speeds. Parent metal was also subjected to fatigue tests.

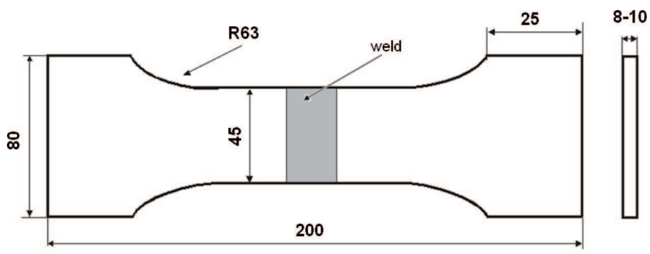

Fig. 4. Shape and geometrical dimensions of fatigue test specimens of FSW joints

According to guidelines of the International Institute of Welding the fatigue strength line crosses a vertical line corresponding to $2x10^6$load cycles. The point of intersection of this straight line with the vertical line representing $2x10^6$cycles determines, on the vertical axis, the value of allowed fatigue strength also known as fatigue category or characteristic value (FAT). In order to calculate FAT, on the basis of the output data presented in the form of a regression line calculated from the following dependence:

$$\log N = \log C - m \log \Delta\sigma \tag{1}$$

where: N – number of cycles, C – material constant, m – straight line slope coefficient, one should determine the straight line slope coefficient and constant logC. Next, one calculates average values from logN and appropriate standard deviations for all experimental data (S_N). The aforesaid data are then used to determine the shift of fatigue strength line. The shift takes into account fatigue safety factor and is calculated from the following dependence:

$$\log N_K = \overline{\log N} - kS_N \tag{2}$$

where: $\log N_K$ – value of shift of logarithm of number of cycles allowing for safety,

$\overline{\log N}$ – average value of logarithm of number of cycles,

k – coefficient (depending on the number of tested specimens),

S_N – standard deviation of logarithms of numbers of cycles.

Hardness tests were conducted with a hardness testing machine Brickers 220, according to PN-EN 1043-1:2000 standard [10]. The tests involved the butt joints which had undergone fatigue tests. The indenter load was 3 kg (HV 3) and indentations were made on specimen cross-sections along 3 measurement lines (line A, B, C) and covered HAZ, thermo-mechanically plasticized zone, weld nugget and fragments of parent metal near HAZ. Line A and C were located 2 mm from the upper and lower edge of specimen and line B was located in the middle of joint thickness. The distance between each measurement point was 2 mm.

4. Investigation

4.1. Macroscopic examination

Test results with reference to joint thickness values are presented in Figure 5. The left side in macrostructure image corresponds to welded joint advancing side.

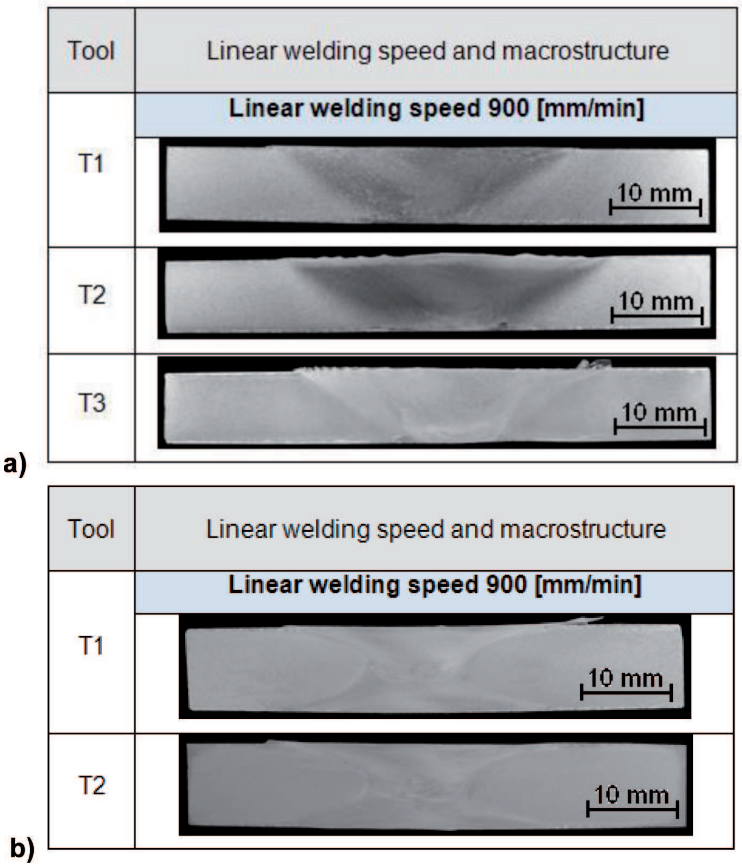

Fig. 5. Macrostructures of FSW welded joints; a) 8 mm-thick single-sided joints, b) 10 mm-thick double-sided joints

4.2. Static tensile test of welded joints

The static tensile test results are presented in Table 2.

TABLE 2
Results of tensile tests of FSW joints at various linear welding speeds and tools

Tool	Joint thickness [mm]	Tensile strength R_m [MPa]		
		Linear welding speed [mm/min]		
		224	560	900
T1	8,0	229,6 ± 1,9	224,2 ± 7,5	242,1 ± 1,2
T2		240,5 ± 2,6	239,6 ± 0,9	243,4 ± 2,2
T3		203,8 ± 9,2	200,6 ± 28,3	228,1 ± 8,8
T1	10,0	213,4 ± 2,5	234,3 ± 2,8	235,6 ± 1,9
T2		211,0 ± 2,1	230,5 ± 0,6	230,2 ± 1,6

Note: In all tests the specimens underwent rupture in the weld

4.3. Fatigue tests

The fatigue test results of the joints are presented in the form of Wöhler's line in Figures 6-13. The FAT calculated for tested joints are presented in Table 3.

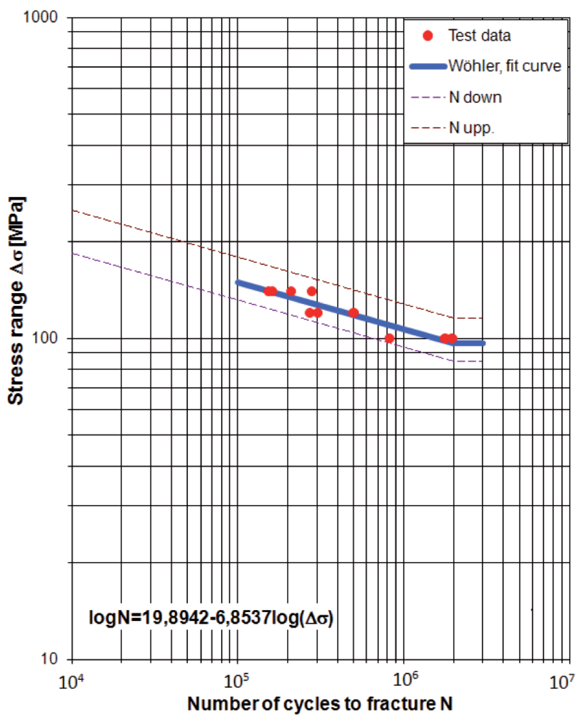

Fig. 6. Wöhler's line for 8 mm-thick joints welded with T1 tool with rough post-weld surface

TABLE 3
Comparison of fatigue categories for FSW joints produced with various tools and in various surface conditions

Type of welded joint	Fatigue category FAT [MPa]		
	T1	T2	T3
Single-sided 8 mm-thick butt joints with machined post-weld surface	66	40	87
Single-sided 8 mm-thick butt joints with rough post-weld surface	53	26	36
Double-sided 10 mm-thick butt joints with machined post-weld surface	75	98	
Parent metal AA6082-T6	148		

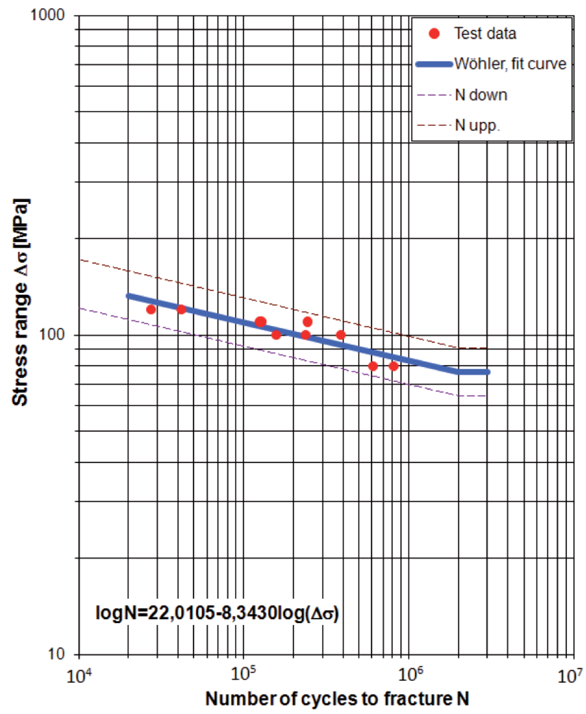

Fig. 7. Wöhler's line for 8 mm-thick joints welded with T1 tool with machined post-weld surface

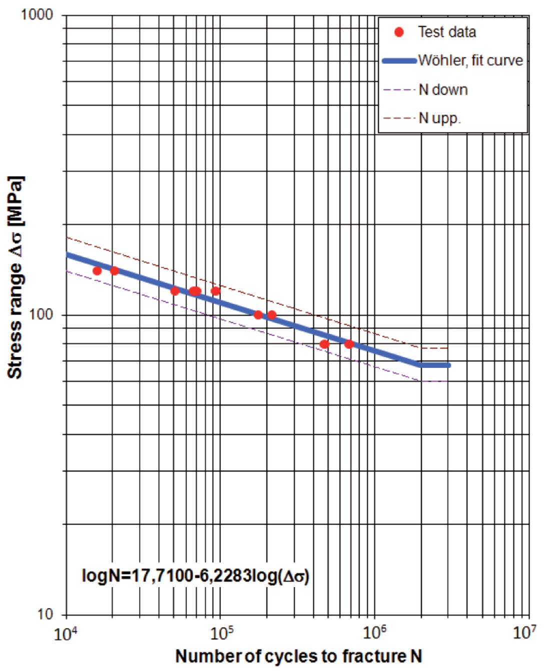

Fig. 8. Wöhler's line for 8 mm-thick joints welded with T2 tool with rough post-weld surface

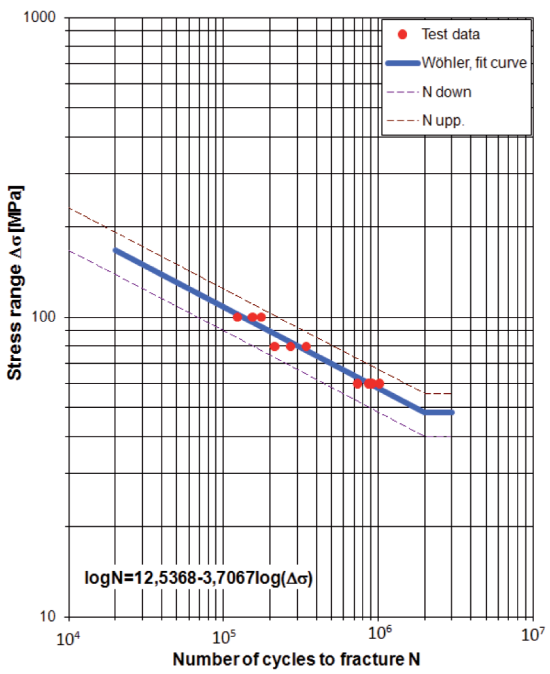

Fig. 9. Wöhler's line for 8 mm-thick joints welded with T2 tool with machined post-weld surface

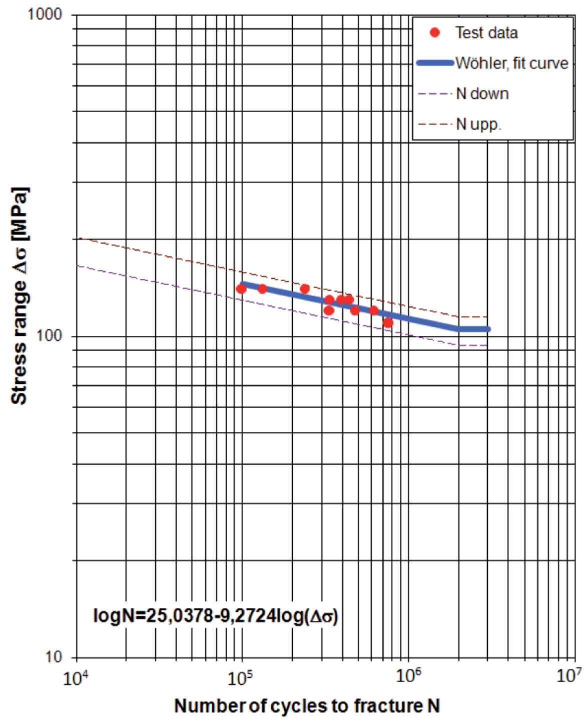

Fig. 10. Wöhler's line for 8 mm-thick joints welded with T3 tool with rough post-weld surface

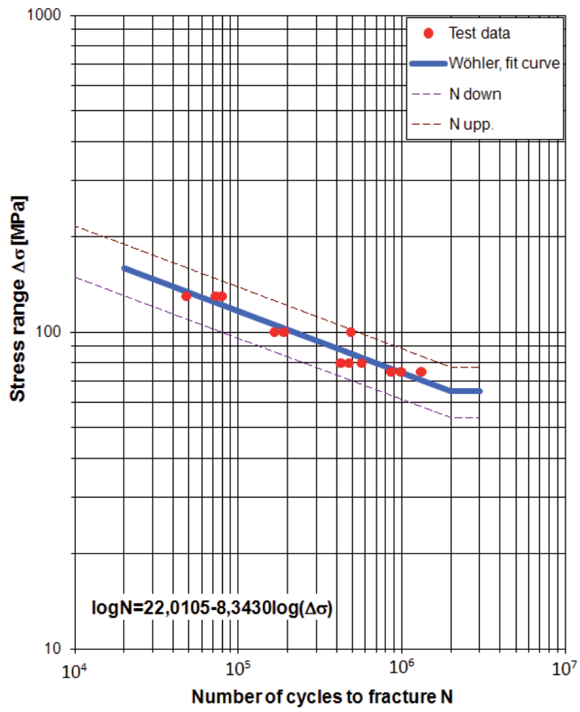

Fig. 11. Wöhler's line for 8 mm-thick joints welded with T3 tool with machined post-weld surface

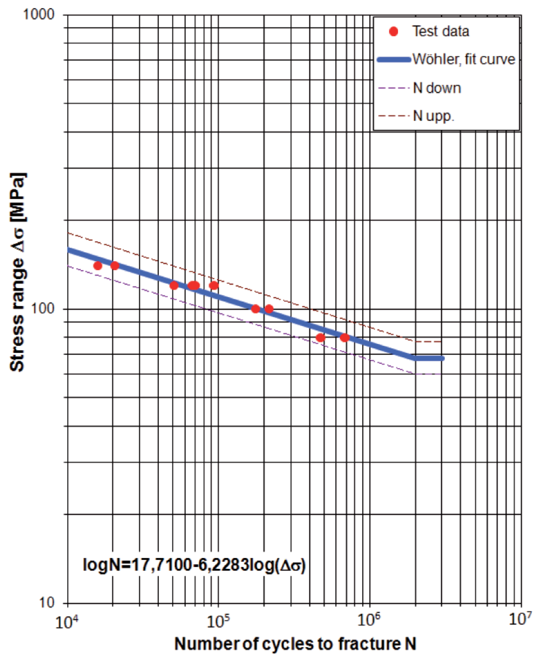

Fig. 12. Wöhler's line for 10 mm-thick joints welded with T1 tool with machined post-weld surface

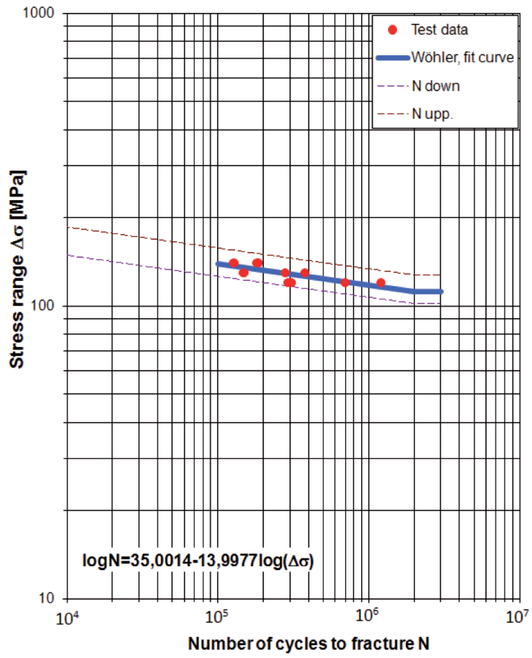

Fig. 13. Wöhler's line for 10 mm-thick joints welded with T2 tool with machined post-weld surface

4.4. Hardness test

The hardness test results are shown in Figures 14-15.

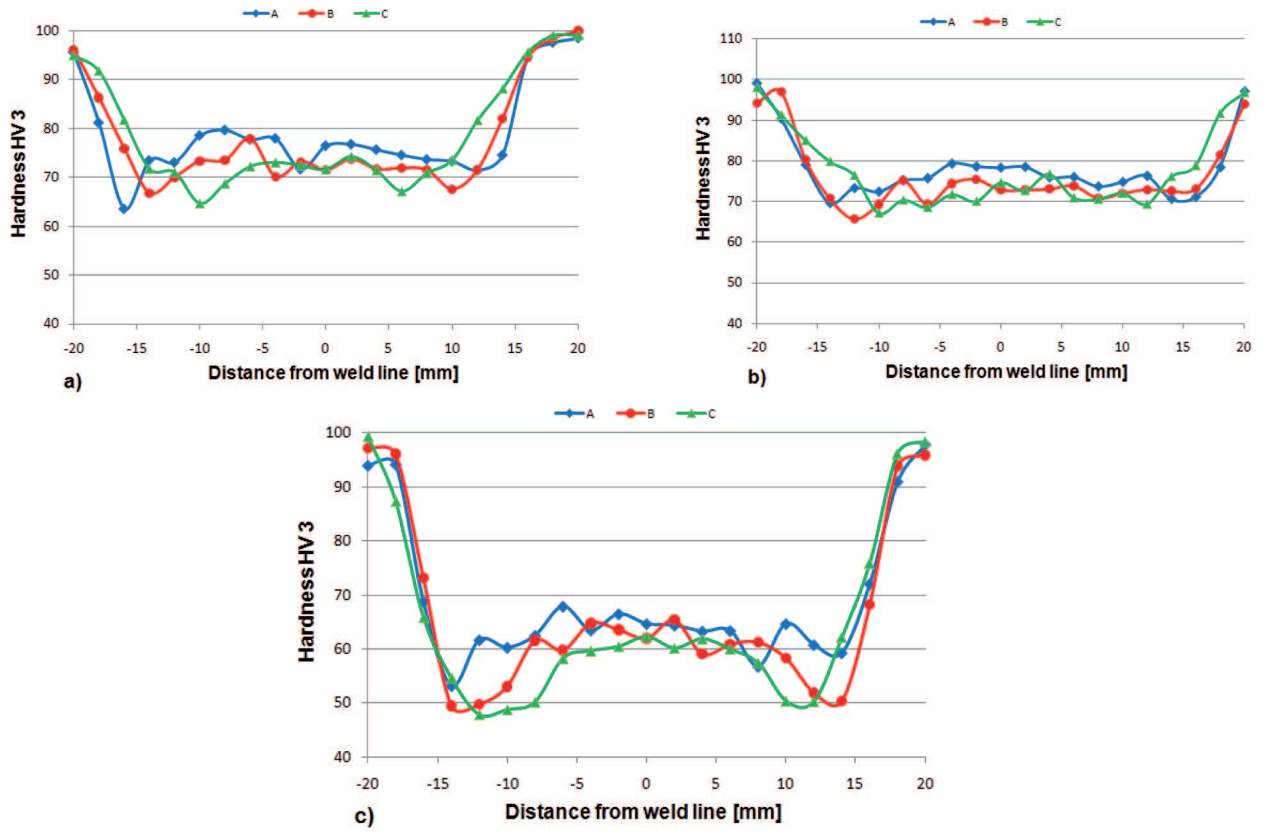

Fig. 14. Hardness profiles for 8 mm-thick FSW single-sided joints produced with tool: a) T1, b) T2, c) T3

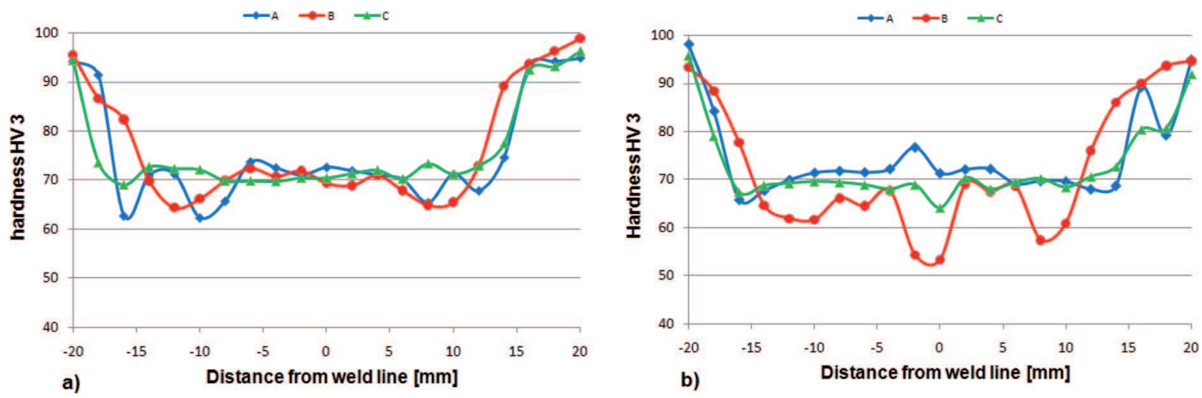

Fig. 15. Hardness profiles for 10 mm-thick FSW double-sided joints produced with tool: a) T1, b) T2

5. Summary

The macroscopic tests proved that within the whole range of linear speeds i.e. from 224 to 900 mm/min, the joints produced with all three types of stirring tool reveal metallic continuity in the weld area. The macrostructure images show that the HAZ width decreases with increasing welding speed. The macroscale observation, however, revealed no distinct changes of joint structure related to applied stirring tools.

The results obtained in the static tensile test of the joints welded with linear welding speeds between 224 and 900 mm/min, with all three types of stirring tools, demonstrate that an increase of welding speed up to 900 mm/min is accompanied by a corresponding increase in tensile strength R_m.

The hardness tests revealed significant hardness differences in joints welded with three different stirring tools. While the differences of hardness values in case of the joints produced with a conventional tool (T1) and Triflute (T2) are insignificant, these values, if compared with hardness values of the joint produced with a tool provided with a smooth probe and shoulder (T3), are considerable. The analysis of the hardness distribution diagram for the joints welded with T3 tool (Fig. 16) reveals that the hardness values are significantly lower than in case of the joints made with tools T1 and T2. Moreover, the hardness distribution in question is more homogenous (without significant hardness jumps) than in the remaining cases. These two observations can undoubtedly be linked to good fatigue strength of these types of joints. Lower hardness values may prove higher joint plasticity; the fatigue crack in the plasticized area tends to develop slower than in the hard and brittle area. More homogenous hardness distribution in the whole thickness of the joint, without abrupt jumps, decreases the inconvenient, from fatigue strength point of view, structural notch.

The comparison of the values of determined fatigue categories (FAT) for 3 types of FSW joints (Table 5) produced with the use of stirring tools featuring different geometric values proves that the simple geometry of the tool, the higher the fatigue strength of the joint. The aforesaid conclusion being true for both single-side and double side welded joints. In case of 8 mm-thick joints, welded with a Triflute tool (T2), the fatigue category (FAT) amounted to 40 MPa. In turn, the application of the tool with the simplest shape (T3) i.e. with a smooth probe and shape resulted in obtaining fatigue strength over 100% higher than that reached with the use of Triflute tool (T2). At the same time, due to the absence of notches (in the form of thread and flutes) in the probe, the tool with a smooth probe and shoulder is more durable and easier to manufacture than a Triflute or a conventional type of tool.

The conducted assessment of the impact of the quality of FSW joint surface on fatigue strength revealed significant differences in fatigue strength values depending on joint preparation manner. The mechanical removal of post-weld marks considerably increases the fatigue strength of joints.

6. Conclusions

1. The fatigue strength of FSW joints made of 6082-T6 aluminium alloy depends on the geometry of a tool applied for welding.

2. The application of the geometrically simplest tool allows to obtain in some cases joints of higher fatigue strength than in case of joints welded with tools of more complicated design.

3. Post-weld marks left by rotating tools travelling along the welding line significantly affect the fatigue strength of FSW joints.

4. The shape of the stirring tool influences the hardness distribution of the FSW joints.

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