MECHANICAL PROPERTIES OF FRICTION STIR-WELDED JOINTS OF $AlCu_4SiMg$ ALUMINIUM ALLOY

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Friction stir welding (FSW) is a new solid-phase technique invented and patented for the butt and lap welding of ferrous and non-ferrous metals. In this article the performance of weld joints which were carried out by FSW and conventional Metal inert gas arc welding (MIG) is studied. A conventional semiautomatic milling machine was used for FSW of EN AW-2014 ($AlCu_4SiMg$) aluminium alloy. The results of tensile, Charpy impact and Brinell hardness tests are used to evaluate the behaviour of welded joints. Low heat input and the absence of melting resulted in excellent mechanical properties, low distortion and better productivity for FSW joints. As it is a solid phase process, FSW permits joining of materials that can not be welded with conventional fusion welding processes.

Key words: friction stir welding, friction welding, new welding technologies

MECHANICKÉ VLASTNOSTI SPOJOV HLINÍKOVEJ ZLIATINY $AlCu_4SiMg$ ZHOTOVENÝCH TRECÍM MIEŠACÍM ZVÁRANÍM

Trecie miešacie zváranie (Friction Stir Welding – FSW) je nový objavený a patentovaný spôsob spojovania feritických a neferitických kovových materiálov v tuhej fáze. Možno ho použiť na zhotovenie tupých a plátovaných zvarových spojov. V článku sú uvedené výsledky štúdia zvarových spojov zhotovených trecím miešacím zváraním – FSW a konvenčným zváraním v ochrane inertného plynu – MIG. Na zváranie spôsobom FSW sa použil bežný poloautomatický frézovací stroj, spojovaným materiálom bola hliníková zliatina $AlCu_4SiMg$ podľa EN AW-2014. Na posúdenie vlastností zvarových spojov sa použili výsledky skúšok ťahom, rázom v ohybe a tvrdosti podľa Brinella. Použitie nízkeho tepelného príkonu a vylúčenie tavenia materiálu umožňujú dosiahnuť vynikajúce mechanické vlastnosti, nízke deformácie a lepšiu produktivitu pre FSW spoj. Keďže je to proces v tuhej fáze, FSW umožňuje spojovať aj také materiály, ktoré sa nedajú zvárať konvenčným zváraním.

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1. Introduction

Friction stir welding was developed and patented by The Welding Institute (TWI-UK) [1]. The technique offers a new, low cost alternative to fusion welding techniques due to the low power requirements, no gas shielding and no special joint edge preparation. The process is repeatable, can be easily monitored and does not produce any major safety hazards, such as fume or radiation [2, 3]. The technique can be used in conjunction with conventional milling machines. Its immediate area of application is for the production of long straight-line welds in welding of aluminium extruded profiles and tailored blanks. The FSW tool is generally made with a profiled pin, which is contained in a shoulder with a larger diameter than that of the pin as seen in Fig. 1. Commonly the tool is shaped with a large diameter shoulder and a small diameter, specially profiled probe that makes contact first as it is plunged into the joint region. The components to be welded are secured to prevent the butted joint faces from being forced apart as the probe passes through and along the seam. For thick plate welding (25–50 mm thick) usually a pilot hole of smaller diameter than the probe is drilled at the start to assist the plunging operation [4]. The depth of penetration is controlled by the length of probe blow the shoulder of the tool. The initial plunging friction contact heats the adjacent metal around the probe as well as a small region of material underneath the probe, but once in contact with the top surface of the substrate the shoulder contributes significant additional heat to the weld region. In addition the contacting shoulder, which can be profiled to provide improved coupling, prevents highly plasticized material from being expelled from the welding region. Once the rotating tool is in position the thermally softened and heat affected zone takes up a shape corresponding to that of the overall tool geometry [5]. The heat-affected zone is much wider at the

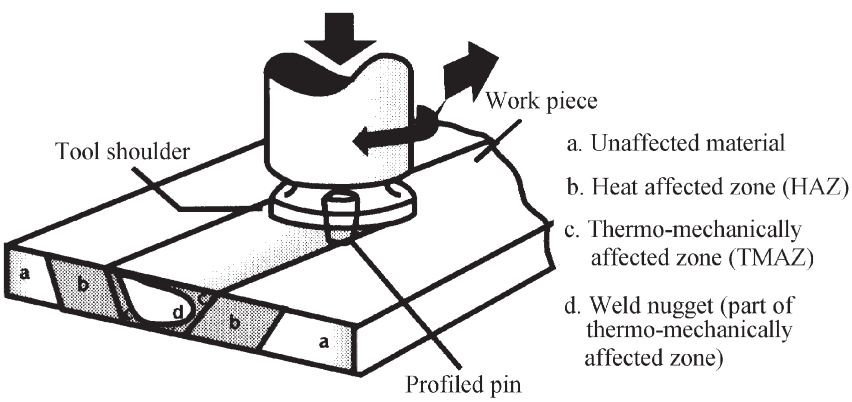

Fig. 1. Friction stir welding principle and microstructure [1].

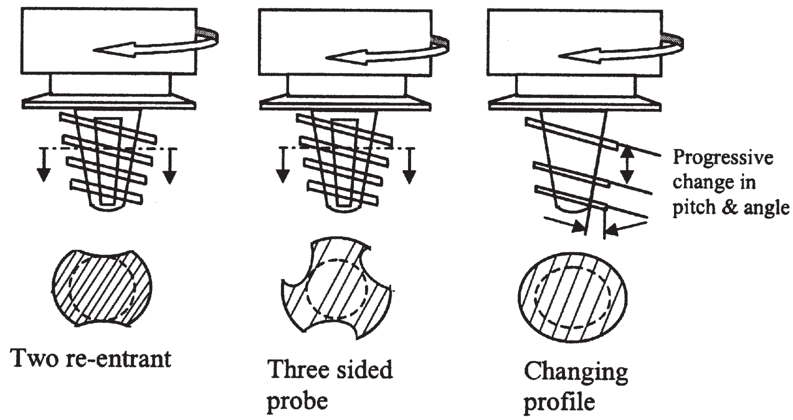

Fig. 2. Basic variants of FSW tools for welding thick work-pieces [3].

top surface (in contact with the shoulder) and tapers down as the probe diameter reduces [6, 7]. The combined frictional heat from the probe and the shoulder creates a highly plasticized "third body" condition around the immersed probe and the adjacent contacting surface of work-piece. This highly plasticized material provides for some hydrostatic effect as the rotating tool moves along the joint, which helps the plasticized material to flow around the tool [8, 9]. The plasticized weld material then coalesces behind the tool as the tool moves away. For butt joining the length of the pin approximates to the thickness of the work-piece if the weld is done from one side. For double-sided weld the length of pin is approximately equal to half of work-piece thickness [10]. The pin is traversed through the joint line while the shoulder is in intimate contact with the top surface of the work-piece to avoid expelling softened material. Basic variants of FSW tools for welding thick materials are given in Fig. 2. The FSW tools are manufactured from a wear resistant material with good static and dynamic properties at elevated temperature. A properly designed FSW tool permits up to 1000 m of weld to be produced in 5 mm thick aluminium extrusions without changing the tool [11]. The onion ring like structure of the nugget is typical of high quality stir weld, in which no porosity or internal voids are detectable. In macro-sections of good quality welds nugget is visible at the centre of the weld, as schematically shown in Fig. 1. Outside the nugget there is a thermo-mechanically affected zone, which has been severely plastically deformed and shows some areas of partial grain refinement [12].

2. Experimental procedures

The tested material is commercial EN AW-2014 ($AlCu_4SiMg$) Al alloy. A number of rectangular work-pieces of 125 mm width, 200 mm length and 10 mm thick were machined out of plates for FSW and conventional MIG welding. FSW was carried out using a semiautomatic milling machine. A pair of work-pieces free from oil films were abutted along a longitudinal section and fastened rigidly on the table of the vertical semiautomatic milling machine. A specially designed rotating tool was machined from stainless steel as seen in Fig. 3 and rotated anti-clockwise and plunged in the work-piece. The rotating tool was fixed to the spindle of the milling machine and spindle of the machine was adjusted at an angle of 1.5 degree away from the spindle's travel path as seen in Fig. 3. Firstly the surface of the work-piece came in contact with the shoulder and the insertion of the rotating tool was stopped. To generate the required pre-frictional heating, the shoulder of rotating tool was held in its initial position for 30 seconds rubbing with the surface of work-piece. Then tool was moved along the joint line. During the experimental studies friction stir welds were carried out at constant tool rotation and traverse speed 800 rpm and 450 mm/min, respectively. Double-sided FSW was applied to the specimens.

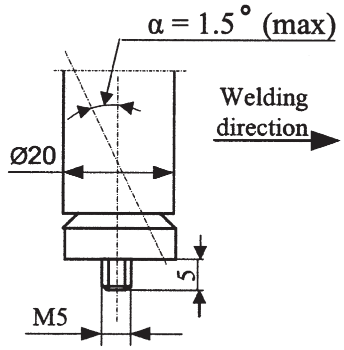

Fig. 3. Rotating tool details used in experiments (dimensions in mm, tool material: stainless steel).

Typically, the surface appearance of FSW is a regular series of partially circular ripples, which point towards the start of the weld. These ripples are essentially cycloidal and are produced by the final sweep of the trailing circumferential edge of the shoulder during traverse. The rotational speed of the tool and the traverse speed of the work-piece determine the pitch between the ripples. The surface colour of FSW is silvery-white for studied material. In order to evaluate the performance of friction stir weld of EN AW-2014 ($AlCu_4SiMg$) aluminium alloy, several tests were employed. The specimens used in mechanical tests were machined out of the welded joint so that the longitudinal rolling direction of the material was parallel to the transverse direction. EN 485-2 is used to dimension test specimens for mechanical tests. The gauge section of tensile test specimens was located within the welded zone and had a size of 200 × 50 × 10 mm. In order to discuss the fracture mechanism, local strain distribution was obtained measuring the change in length by preliminarily stamped points. Charpy impact tests with V-notch, according to EN 10045-1 were carried out. The microstructure of welded joints was evaluated by measuring hardness distribution on the surface of a weld perpendicular to work-piece transverse direction and along a line drawn on the cross section of the weld.

The process was also compared and assessed for distortion and productivity with alternative conventional MIG fusion welding.

3. Results and discussion

The tensile test was applied to base metal, FSW and MIG welded specimens, respectively. Ultimate tensile strength of FSW joint was almost at the same level as that for the base metal. The strength of the FSW is 50 % greater than MIG weld. The elongation values are 16 %, 14 %, 4 % for base, FSW, and MIG welded

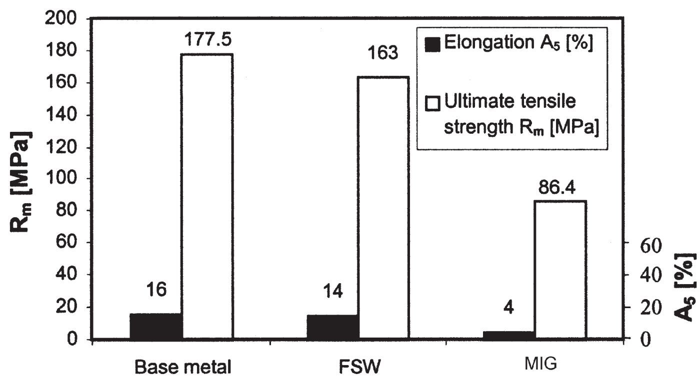

Fig. 4. Comparison of mechanical properties of FSW, MIG and base metal (FSW: friction stir weld, MIG: metal inert gas arc welding, base metal: EN AW-2014 ($AlCu_4SiMg$) aluminium alloy).

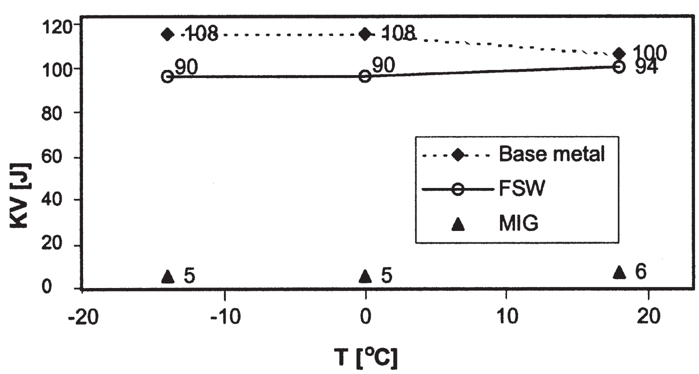

Fig. 5. Impact strength of FSW, MIG and base metal (FSW: friction stir weld, MIG: metal inert gas arc welding, base metal: EN AW-2014 ($AlCu_4SiMg$) aluminium alloy).

specimens respectively as seen in Fig. 4. Because it is a solid state process the FSW welded areas do not have a cast structure, but rather a refined structure. The obtained welds by FSW technique were mechanically superior to the conventional process.

The impact toughness of base metal, FSW and MIG welded specimens were defined by Charpy impact test. Tests were carried out at room temperature at

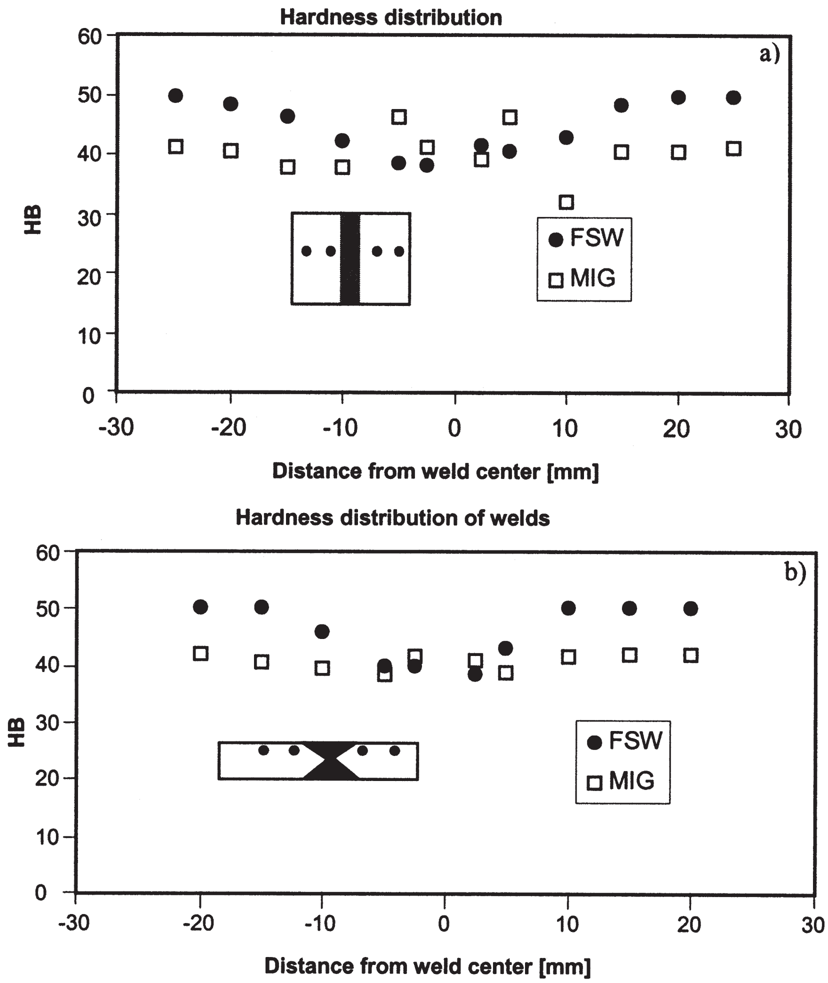

Fig. 6. Hardness distribution of FSW and MIG welded specimens (a – on the surface of weld, b – on the cross section of weld).

different specimen temperature. The impact toughness of FSW is only 6 % lower than that of parent metal and 16 times greater than that of joints welded by MIG. When it is compared with MIG welding, the “stirring” of the aluminium alloy during FSW gives it a finer microstructure, which improves its resistance to impact. In contrast, MIG welds have a coarse columnar crystalline structure. The results of the Charpy impact tests are shown in Fig. 5. Hardness distribution of FSW and MIG welded specimens are shown in Fig. 6. Figure 6a shows hardness distribution on the surface of weld perpendicular to work placement transverse direction. In Fig. 6b, hardness distribution along a line drawn on the cross section of the weld is given. Figures show that the region where hardness decreases is narrower for FSW than MIG weld. The ratio of hardness decrease is smaller for FSW than MIG weld. The width of the region, where mechanical properties are affected, can be also reduced selecting a smaller diameter for friction tool.

FSW and MIG welded specimens were compared for dimensional accuracy. Friction stir welded specimens resulted in better dimensional accuracy because the materials are not melted during the welding process. It is known that the maximum temperature that for aluminium FSW welds at is 480 ℃, far lower than that of MIG welding [13]. Increase in the temperature during welding results in greater distortion. The amount of distortion is only one-twelfth of that in MIG welding. A comparison of the amount of distortion and shortening for two welding methods is shown in Fig. 7. When both FSW and MIG welding processes are compared with each other for production rate, the results show that FSW has higher performance in the production rate and quality, as well as decrease in the production costs. Welding speed of FSW and MIG welding process is given in Fig. 8.

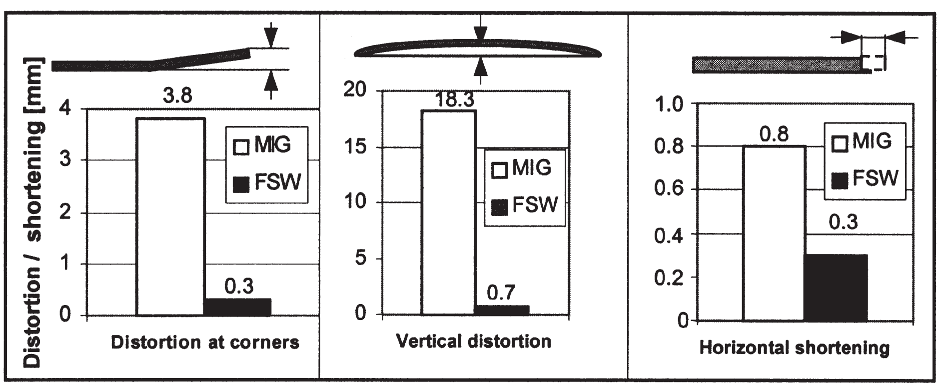

Fig. 7. The amount of distortion/shortening in FSW and MIG welding.

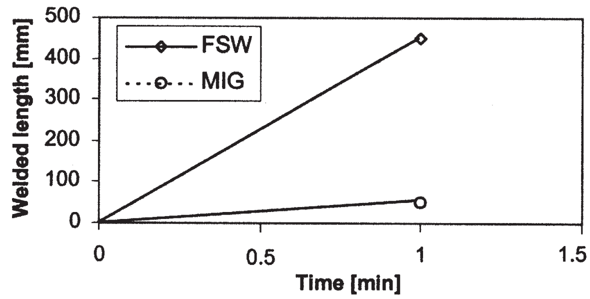

Fig. 8. Comparison of FSW and MIG welding processes for welding speed.

4. Conclusion

From the results presented above, the following conclusions can be drawn:

– Mechanical tests have confirmed that the mechanical properties of FSW joints compare well with parent material.

– The FSW technique can be used in conjunction with conventional milling machine. The development of robotized FSW heads could extend the range of application into three dimensional components.

– The process is machine tool technology based, which can be semi- or fully-automated.

– The surface appearance approaches to that of a rough-machined surface. This situation reduces production costs in further processing and finishing.

– The process does not normally require shielding gas.

– No consumable material is required.

– The process can be applied to one or two sided joints.

– Welding is carried out without spatter, ozone formation, or visual radiation associated with fusion welding techniques.

– The process is solid-phase with process temperature regimes lower than fusion techniques, thus avoiding problems, which occur with the liquid phase such as alloy segregation, porosity, cracking, and distortion.

– No special joint is required (only nominally square edged abutting plates are needed for a butt joint) so it saves consumable material, time and money.

Drawbacks of the process:

– It is necessary to clamp the work-piece materials firmly. Suitable jigging and baking bars are needed to prevent the abutting plates moving apart or material breaking out through the underside of the joint.

– Different length pin tools are required when welding materials of varying thickness. At the end of the weld the pin left a keyhole. To overcome this problem a special tool may be designed which has an automatically retractable pin into the shoulder.

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