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MECHANICAL PROPERTIES OF WELDS OBTAINED BY BOBBIN TOOL FRICTION STIR WELDING PROCESS

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Abstract

Friction Stir Welding (FSW) is a relatively new and challenging solid-state welding technique that is getting increasingly popular today. In this paper, the aluminium-magnesium alloy was welded by the Bobbin tool Friction Stir Welding (BTFSW) process, which, contrary to conventional FSW, uses a special tool with two shoulders. The bottom shoulder replaces the backing plate and forms the root of the weld, enabling the omittance of some defects and a simplified process apparatus. Tool rotary speed was varied, to find the optimal parameter from the point of view of macro and mechanical properties: tensile, bend testing, as well as the testing of impact energy.

Keywords: Friction Stir Welding; Bobbin tool, Welding Parameters, Welding Characterization

1. Introduction

Friction Stir Welding (FSW) is a solid-state welding process that utilizes a special spindle-shaped tool that imparts friction to heat, soften and stir the material and thus form the weld bead [1–4]. This welding procedure is developed and patented at the beginning of the 1990s in the United Kingdom at The Welding Institute (TWI) [2,5–9]. FSW process schematics can be seen in Figure 1.
The rotating tool is in contact with the base material (BM), from this contact between the tool and BM, heat is generated. This friction-generated heat softens the BM and enables the flow of the softened material, because of the tool rotation and friction, the tool mixes BM plates one into another, thus forming the welded joint.

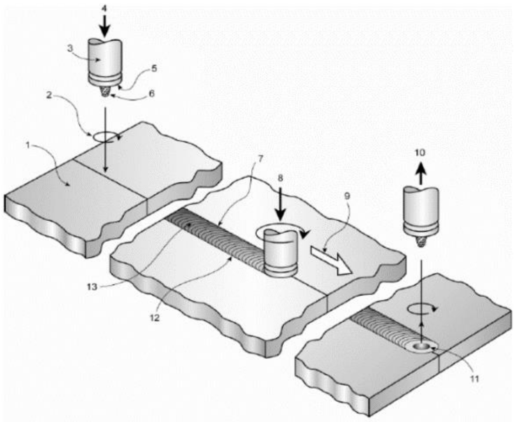

Figure 1. Friction Stir Welding nomenclature, 1-Base metal, 2-Direction of tool rotation (clockwise), 3-Weld tool, 4-Downward movement of the tool, 5-Tool shoulder, 6-Probe, 7-Advancing side of the weld, 8-Axial force, 9-Direction of welding, 10-Upward movement of the tool, 11-Exit hole, 12-Retreating side of the weld, 13-Weld face [4,10].

This process was predominantly used to weld aluminium and its alloys that are considered not possible to weld using the melting procedures of welding [6,11]. Soon after perfecting the technology, it was applied to other metal materials such as copper [12,13] and even steel [14]. FSW welding procedure is also very suitable for welding dissimilar materials (e.g., copper to steel) [8,12,13,15]. Since its beginning, FSW was a very attractive welding procedure applicable in various industries like aerospace, shipbuilding, train, building, etc. [14,16–18]. In parallel, new variations of the FSW procedure have appeared: Friction Stir Spot welding (FSSW), Steady shoulder FSW (SSFSW), Bobbin tool FSW (BTFSW), Self-reacting FSW, Friction Stir Riveting (FSR), etc. [17].

Bobbin Tool FSW (BTFSW) is one of the newer iterations of the FSW (now often called conventional FSW or CFSW). BTFSW tool is unique because it features a double (upper and lower) shoulder geometry presented in Figure 2. In BTFSW, the base material is clamped between the shoulders of the tool during the welding process, and it can be established that BM is heated from both sides resulting in more efficient joints in comparison to CFSW welding process. This may result in potentially better quality of welded joints and free of defects such as incomplete penetration, linear mismatch, etc. Also, BTFSW has a simpler configuration, with backing plate omitted, since its role is taken by the bottom shoulder of the tool [19].

In this work, the optimization of the bobbin tool rotational speed was performed in order to obtain adequate mechanical properties in Al-Mg alloy weld. A range of mechanical properties was tested, beginning with tensile, then bend and impact tests, which were correlated to metallographic examinations.

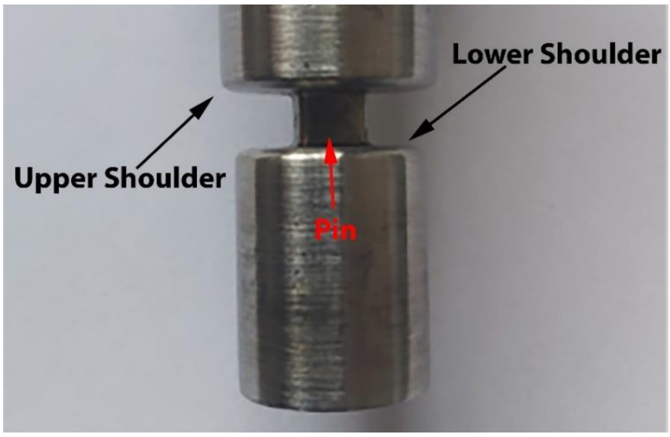

Figure 2. Bobbin tool FSW geometry [20]

2. Experimental

Welding of the samples is performed on the vertical milling machine (Prvomajska FSSGVK-3) adjusted for FSW. The experimental setup can be seen in Figure 3.

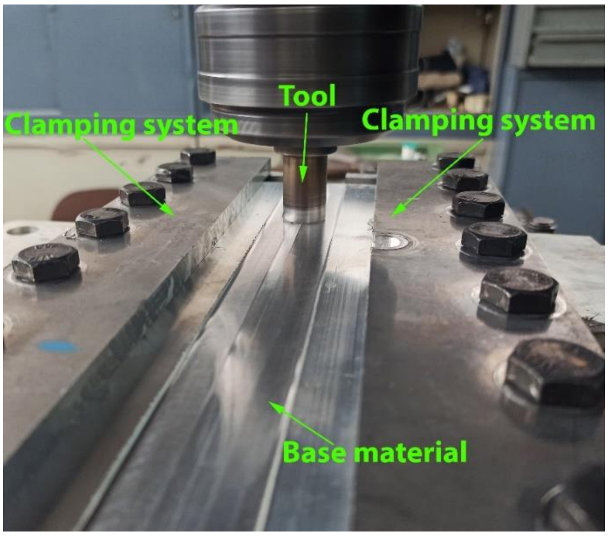

Figure 3. Experimental setup

The welding parameters used in the experiment are presented in table 1.

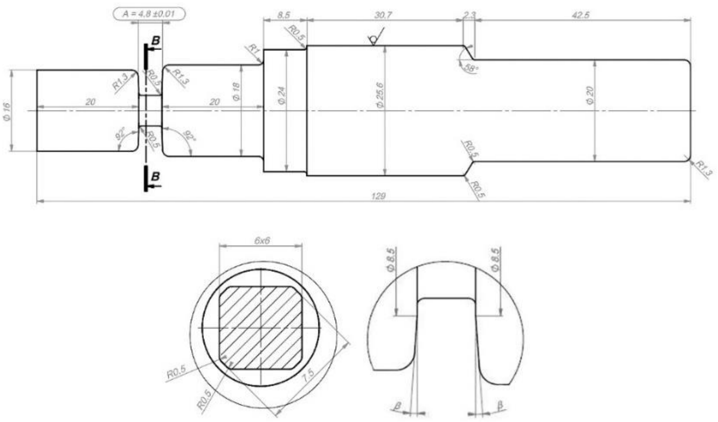

Figure 4. Toolp used: in tool A2, β_1=2°

Table1. Tool and parameters designation system

Weld designation	Tool shoulder angle [°]	Tool rotation speed [rpm]	Welding speed [mm/min]
9		900	21
11	2	1120	21
14		1400	21

The tool was made from X40CrMoV5-1 (AISI H13) hot work tool steel. It was quenched and tempered and after that, the tool obtained a hardness of 53 HRC. The drawing of the tools is presented in Figure 4.

Welding material for the experiment was AA5005-0 in plates having the dimensions 140 × 60× 4.8 mm. The chemical composition of the base material is presented in Table 2. It was obtained by ARL 3580 (Thermo Scientific, Waltham, USA) optical emission spectrometer (OES). Tensile properties were tested on the universal tensile testing machine (VEB ZDM 5/91) and the results are presented in Table 3.

After the welding, plates were cut in accordance with the cutting plan presented in Figure 5. After which the samples were tested.

Table 2. Chemical composition of the base material

%	Cu	Mn	Mg	Si	Fe	Zn	Ti	Al
Base material	0.05	0.12	0.56	0.25	0.31	0.057	0.03	Balance

Table 3. Mechanical properties of the base material.

Rp [MPa]	**Rm [MPa]**	**A [%]**	**Z [%]**
113	127	25	63

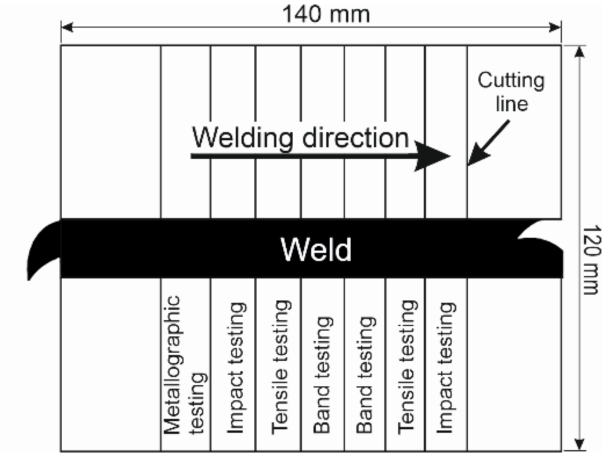

Figure 5. Cutting plan

Testing of the samples included: metallography analysis, tensile testing, three-point bending, and instrumented Charpy impact testing. Metallographic samples were prepared by grinding (abrasive SiC papers from P150 to P2500 grit) and polishing (diamond suspensions with 6, 3, 1 and ¼ µm), and finally, etching was done with a solvent of 1 ml of Hydrofluoric acid and 24 ml of distilled water. Weld defects were analysed with a Leitz Orthoplan light microscope.

Tensile testing was carried out in accordance with EN ISO 4136:2012 standard on VEB ZDM 5/91 testing machine. Ultimate tensile strength, proof strength, and cross-section reduction were measured, and average values were reported. Three-point bend test was also performed on the VEB ZDM 5/91 machine in accordance with EN ISO 5173:2009 in two specimens, one over the face of the weld, and the other over the root of the weld until reaching 180° of the bend angles. The Charpy impact test was performed in accordance with EN ISO 148-1:2016 standard on instrumented Charpy pendulum JWT-450 (Jinan, Jinan, China), at room temperature. Standard V – notch in the Charpy specimens was placed in the nugget zone (NZ) due to the characteristic hourglass shape of the weld.

3. Results and discussion

3.1. Metallographic examinations

Macrographs of welded samples are presented in Figure 7. A distinct hourglass shape of the welded typical for the BTFSW joining process can be seen, obtained by the special two-shoulder tool shape, forming both sides of the weld. It contains the common nugget zone (NZ) and thermomechanically affected zone (TMAZ). Heat affected zone (HAZ) is between TMAZ and base metal. In specimen 14, a tunnel or a cavity can be observed (200 type imperfection), 0.86 x 0.4 mm in size. That means, specimen 14 complies with EN ISO 25239-5:2020 standard, acceptance level C. On the other hand, specimens 9 and 11 that contain no cavity comply with the stricter B acceptance level.

The microstructure of the base metal (BM) is shown in Figure 7a, with distinct uniform grains. Highly refined predominantly uniaxial grains are present in the NZ, Figure 7b. NZ/TMAZ transition zone is presented in Figure 7a, while TMAZ/HAZ zone is shown in Figure 7d. As with conventional FSW process, grains in TMAZ are elongated, the result of deformation and heat effect of the BTFSW tool.

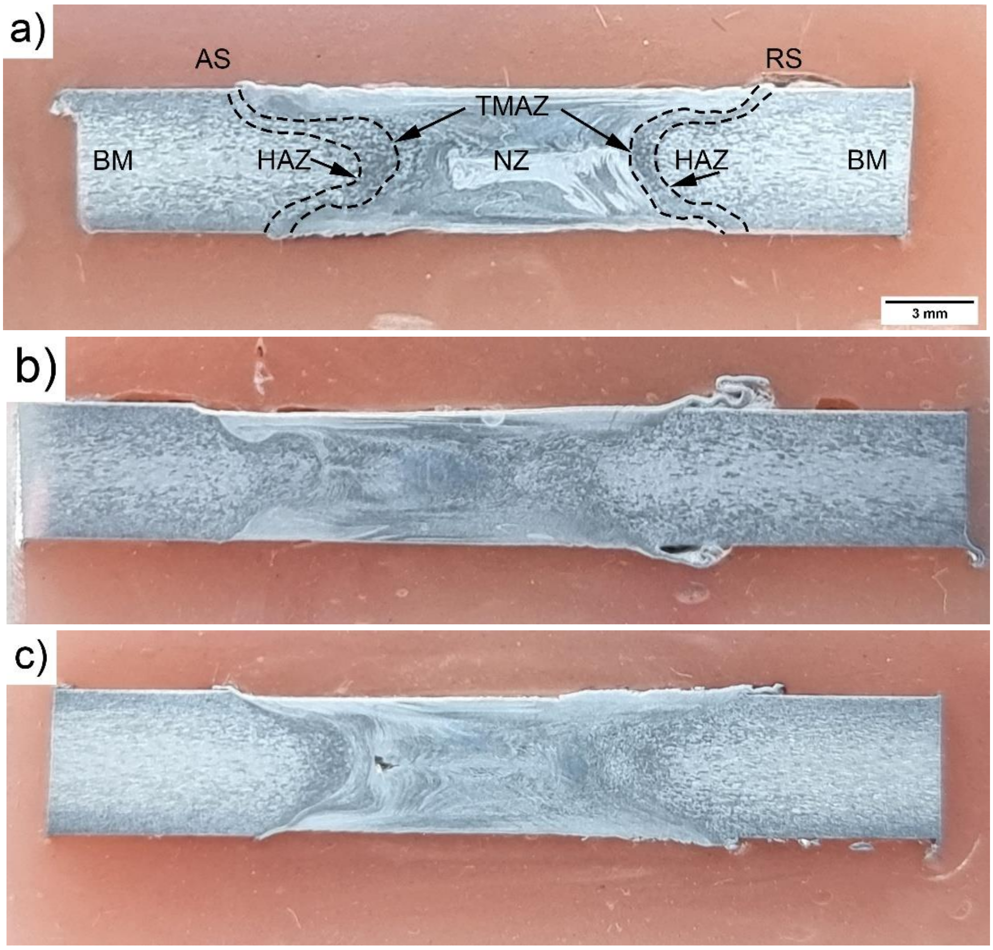

Figure 6. Cross-sectional micrographs of specimens: a) 9; b) 11; c) 14

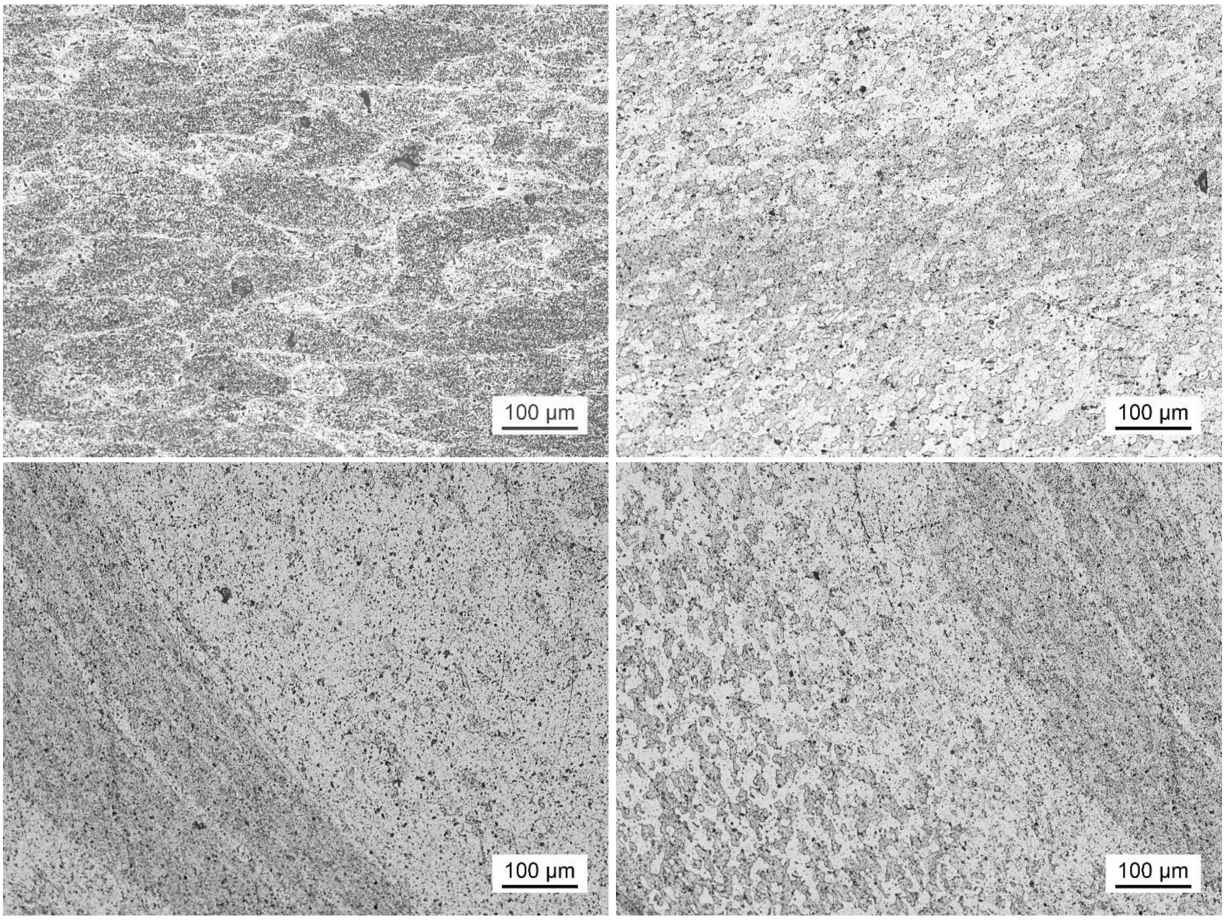

Figure 7. Microstructure of the base material (a), nugget zone (b), transition NZ/TMAZ (c), transition TMAZ/HAZ (d) in specimen 9

3.2. Mechanical properties

Mechanical properties of obtained BTFSW welds are presented in Figures 8 - 10. The results of tensile testing are shown in Figure 8. The highest tensile strength was obtained in specimen 11, while the lowest was obtained in specimen 14. This is the result of cavity, which influences a drop in strength and represents a weakening spot, in other words, a crack initiation site. The cavity can be clearly seen in Figure 6c, however, a relatively high standard deviations indicate that the cavity size and dimensions vary along the length of the weld. On the other hand, strain hardening plays the dominant role in decreasing the reduction in area compared to base material.

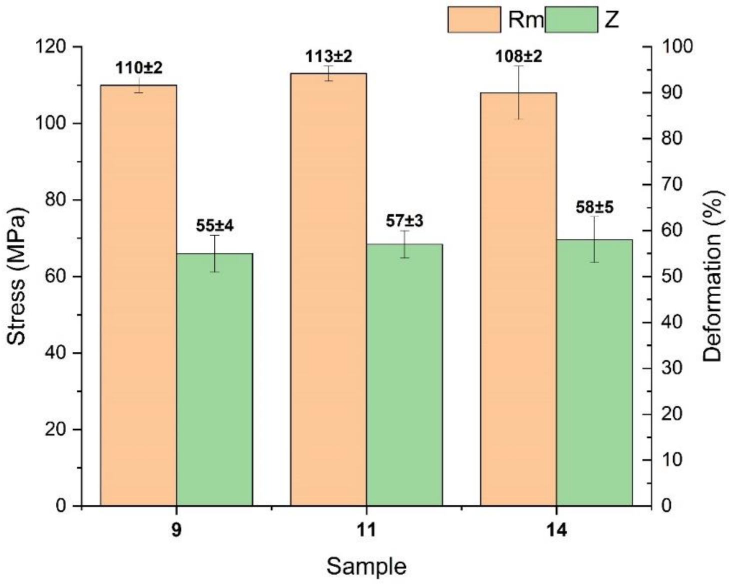

Figure 8. Tensile testing results

Bend testing results of specimens bent over the weld area formed by the bottom shoulder are shown in Figure 9. No cracks occurred, even in specimen 14 with cavity, indicating a relatively high ductility in the nugget zone. A relatively high ductility is indicated by impact strength results shown in Figure 10. All three welds exhibit a higher overall impact strength compared to base material. Furthermore, crack initiation and crack propagation energies in all specimens are also higher than the corresponding values obtained in base material.

This trend is in contrast to the results of reduction in area of welds obtained in tensile testing, which is lower in compared to base material. This can be explained by the fact that tensile tested specimens fractured in the HAZ/TMAZ interface, where the microstructure is different and coarser compared to the one in the NZ.

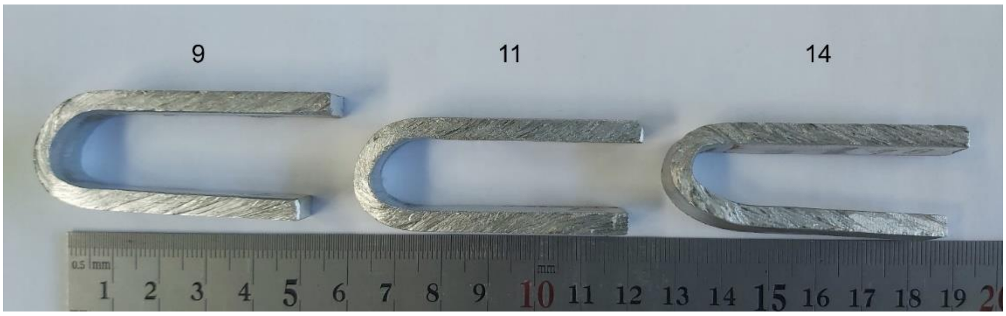

Figure 9. Bent specimens.

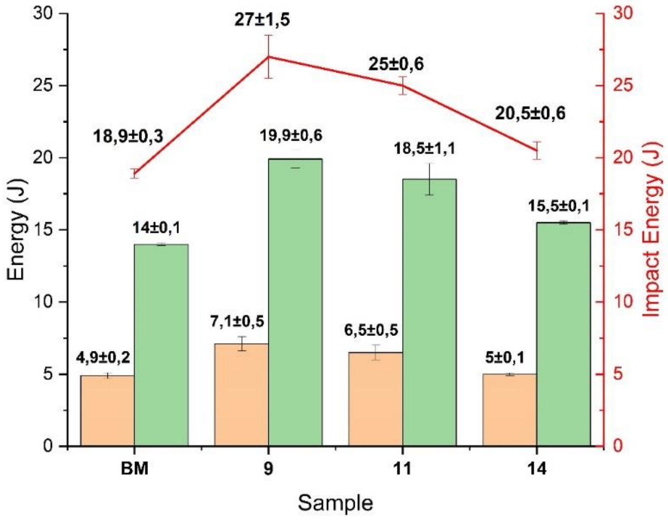

Figure 10. Impact energy results

4. Conclusions

Based on the results presented in this work, and within the limitations of experimental setup, the following conclusions can be drawn:

- BTFSW process has a significantly simplified setup compared to conventional FSW, avoiding the backing plate, replacing it with the bottom shoulder of the tool.
- The weld shape has a distinct hour-glass shape, which is in contrast to the V-shaped weld in conventional FSW.
- The bottom shoulder of the tool enables the weld root defects to be avoided. Even if the cavity occurs, the refined grain in the nugget enables the bending of the weld to the full 180^o.
- The range of tool rotation speed of 900 to 1400 rpm proved to be adequate for obtaining EN ISO 25239-5:2020 standard compliant welds.
- The optimal rotational speed was 1120 rpm, enabling the highest tensile strength of the weld, combined with increased weld impact strength.

5. Acknowledgments

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