DOI: https://doi.org/10.37434/tpwj2024.02.03

STRENGTH AND STRUCTURE OF MA2-1M MAGNESIUM ALLOY BUTT JOINTS PRODUCED BY ARGON-ARC WELDING WITH A NONCONSUMABLE ELECTRODE AND BY FRICTION STIR WELDING

A.G. Poklyatskyi[1], V.E. Fedorchuk[1], S.I. Motrunich[1], Yu.V. Falchenko[1], M. Sahul[2]

[1]E.O. Paton Electric Welding Institute of the NASU
11 Kazymyr Malevych Str., 03150, Kyiv, Ukraine
[2]Czech Technical University
166 36, Prague, Czech Republic

ABSTRACT

The paper analyzes the results of research of structural features and tensile strength of butt joints of 2 mm thick sheets of structural MA2-1M magnesium alloy produced by nonconsumable electrode argon-arc welding and by friction stir welding. It is shown that in friction stir welding as a result of intensive plastic deformation of the metal, a fine crystalline structure is formed in the welds. It was determined that microhardness of the metal in such a welded joint has minimal values in the zone of thermomechanical impact on the retreating side near the heat-affected zone, where fracture of the specimens occurs during their static tension. Tensile strength of specimens of welded joints produced by friction stir welding, and specimens with root penetration removed to the level of the base material and additionally scraped reinforcement of welds produced by fusion welding, is at the level of 233–236 MPa, which amounts to ~84 % of this value for base material.

KEYWORDS: magnesium alloy, friction stir welding, argon-arc welding, structure, microhardness, strength

INTRODUCTION

Magnesium alloys are widely used as structural materials to manufacture lightweight strong components of aerospace and automotive equipment, as well as moving elements of textile and printing equipment, which allows reducing the force of inertia at high speeds of their movement [1–3]. The effectiveness of such alloy application is due to a low specific weight of magnesium (1.74 g/cm^3), high strength of its alloys (228–290 MPa) and their considerable heat resistance (up to 450 °C) [4].

The majority of magnesium alloys are successfully welded by fusion welding methods. Similar to aluminium alloys, nonconsumable (tungsten) electrode argon-arc welding (GTAW) is most often used. Welded joints of magnesium alloys produced by fusion processes are characterized by the same defects in the form of pores, macroinclusions of oxide films and hot cracks, which arise in aluminium alloy welding [5, 6]. Therefore, friction stir welding (FSW) is a promising method for producing sound permanent joints of magnesium alloys [7]. The abovementioned defects can be avoided due to weld formation in the solid phase, without melting of the edges being welded. Moreover, FSW does not require filler wire (manufacture of which is complicated by high brittleness of magnesium alloys) or shielding inert gas, which increases material cost savings [8].

Experimental investigations conducted by foreign specialists are indicative of the efficiency of application of this welding method for magnesium alloys. The produced joints have fine-crystalline structure of the welds and high mechanical properties [9, 10].

The objective of this work is investigation of structural features and determination of mechanical properties of welded joints on 2 mm sheets of structural MA2-1M magnesium alloy, produced by GTAW and friction stir welding.

INVESTIGATION PROCEDURE

Mechanical properties of welded joints were assessed using 2 mm sheets of serial MA-21M magnesium alloy of Mg–Al–Zn–Mn alloying system, which in addition to magnesium contains, wt.%: 4.5 Al, 0.95 Zn, 0.47 Mn, 0.3 Fe, 0.06 Si, 0.01 Cu. Mechanical properties of such sheets are given in the Table 1.

The process of mechanized GTA welding was conducted in ASTV-2M unit with MW-450 power source (Fronius, Austria). Square-wave current of 200 Hz frequency was used [11] for intensive stirring of weld pool molten metal, creating favourable conditions for its degassing and reducing the probability of pore formation in the welds. The nonconsumable electrode diameter was 3.2 mm, and the length of its extension was 4 mm. The torch movement speed of 20 m/h was selected, considering on the one hand the wish to ensure the minimal thermal impact on the metal being welded, and on the other hand, the possibility for the welding operator to adjust the electrode orientation relative to the butt axis or the arc length, if required. To obtain chemical composition of the weld metal close to that of the base material, a strip from base material 2 mm thick was used as the filler material to form the weld reinforcement. The strip was fixed between the edges being welded, lowering it to the bottom of 1 mm deep and 4 mm wide groove. The height of this strip was 6–7 mm, which ensured formation of the required weld reinforcement. The possible defects characteristic for this welding process, which have the form of pores and macroinclusions of oxide films, mostly arising in the weld root part, come to the root penetration, which is scraped flush with the base metal in critical structures. Mechanical cleaning of the edges to be welded (from three sides) and of filler material strip (from four sides) to the depth of 0.10–0.12 mm was performed immediately before welding. To ensure a reliable protection of the metal from oxidation, high grade argon was used in the welding zone. The inner diameter of the protective ceramic nozzle was 16 mm, and gas flow rate was 20–22 l/min. Sound weld formation under such conditions was ensured at the current of 145–150 A. Current reduction led to incomplete fusion of the filler material strip placed into the butt with the base material, and current increase resulted in violation of weld formation.

FSW of the studied alloy sheets was performed in a laboratory unit developed at PWI. It ensures the speed of the tool linear movement along the butt (welding speed) in the range of 8–38 m/h, and constant frequency of its rotation of 1420 rpm. A special tool of our design [12] with shoulder diameter of 12 mm and 1.85 mm long pin in the form of a truncated cone of 3.4 mm diameter at the shoulder base was used for welding. Butt joints of the sheets were produced at three welding speeds of 8, 16 and 24 m/h for evaluation of their properties. At higher welding speeds the probability of internal defect occurrence in the welds in the form of cavities characteristic for this process, becomes higher [13]. More over, in the laboratory unit tool pressing to the surfaces of the edges being welded is performed by the welding operator using a support, which makes the uniformity of its regulation more complicated at higher welding speeds. Mechanical cleaning of the edges to be welded (from three sides) to the depth of 0.10–0.12 mm was performed directly before welding to prevent penetration of possible surface contamination or oxide films into the weld formation zone.

Table 1. Mechanical properties of 2 mm sheets of structural MA2-1M magnesium alloy

Characteristic	Specimens cut out along the sheet rolling direction	Specimens cut out across the sheet rolling direction
σ_t, MPa	279–274 / 277	283–279 / 281
$\sigma_{0.2}$, MPa	200–179 / 187	219–203 / 210
δ_5, %	20.3–19.5 / 19.9	26.3–23.5 / 25.0
α, deg	38–32 / 35	45–38 / 42

Note. The numerator shows the maximal and minimal values, and the denominator gives their average values by the results of testing three specimens.

The produced welded joints were used to make sections for studying the structural features of the welds and for assessing the degree of metal softening in the welding zone. Metal microhardness was measured on the section end faces by PMT-3 microhardness meter. Assessment of structural features of the welded joints was performed using MMT-1600B optical microscope. Determination of tensile strength at uniaxial tension of specimens with working part width of 15 mm was conducted in keeping with DSTU EN ISO 4236x in an all-purpose servohydraulic complex MTS 318.25. GTA welded samples were tested with both excess penetration cut off flush with the base material, and with the additionally scraped weld reinforcement.

RESULTS AND DISCUSSION

Analysis of the microstructure of FSW joint showed that it consists of welding zones classical for such a welding method: base material, thermomechanical impact zone, HAZ and weld metal with the formed nugget (Figure 1). Weld metal grains are 3–5 times finer than those in the metal being welded. The most fine-grained structure is observed in the weld metal nugget. Measurements of metal microhardness in the transverse sections in different zones of FS welded joint showed that its values are minimal in the thermomechanical impact zone from the retreating side near (2.5–3.0 mm) the HAZ (Figure 2). Accordingly, at static tension of specimens of such welded joints, they failed in the thermomechanical impact zone from the retreating side (Figure 3). On the face side fracture occurred exactly at the distance of 2.5–3.0 mm from the boundary of this zone with the HAZ, and from the root side it ran in the zone of the weld transition

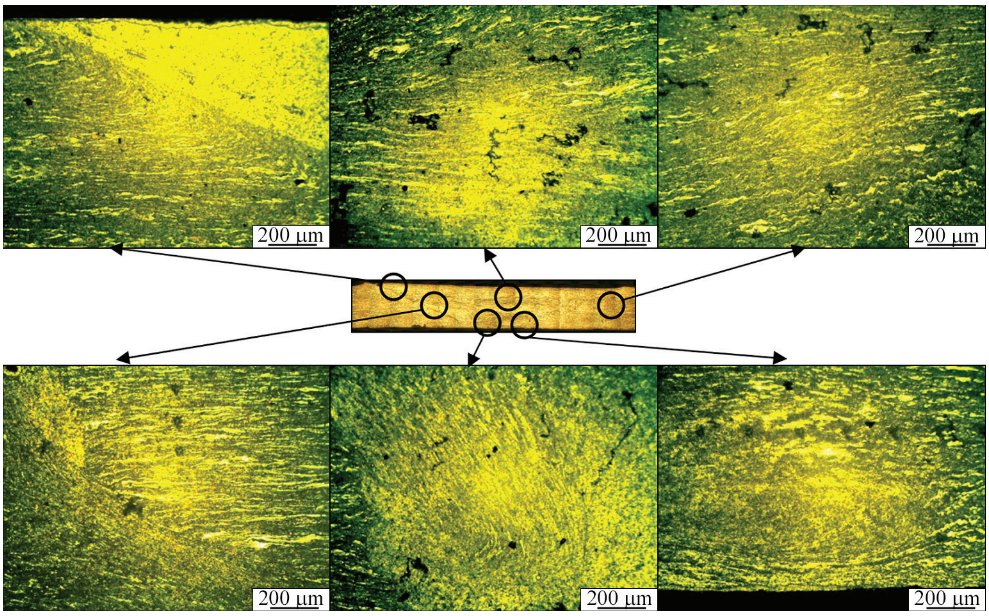

Figure 1. Fragments of the microstructure of FSW butt joint of structural MA2-1M magnesium alloy

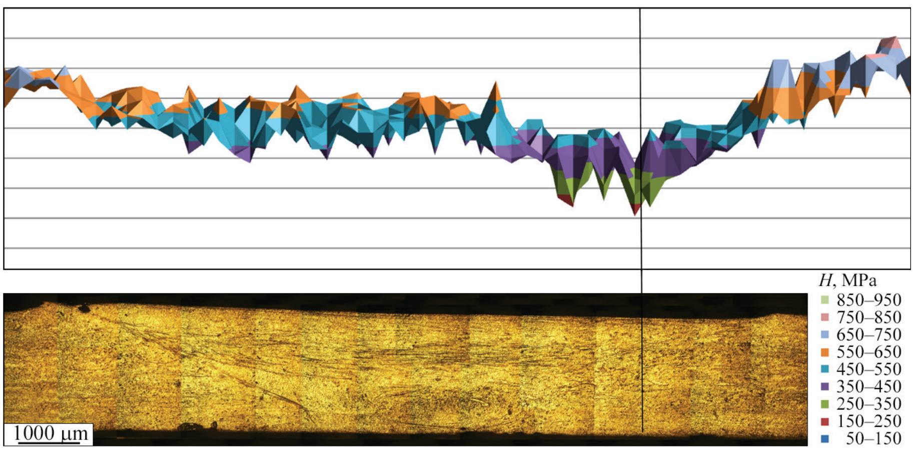

Figure 2. Metal microhardness in different zones of FS welded joint of 2 mm MA2-1M alloy produced at welding speed of 14 m/h

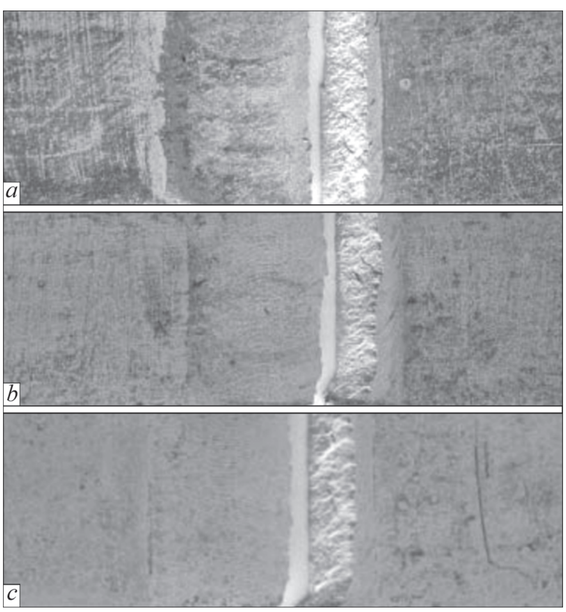

Figure 3. Appearance of the face surface of working part of 2 mm MA2-1M magnesium alloy specimens fractured as a result of static tension, which were produced by FSW at welding speeds of 8 (*a*), 16 (*b*) and 24 m/h (*c*)

to base material. The tensile strength of FS welded specimens is at the level of 234–236 MPa, and it is independent on the welding speed in the studied range.

Microstructural studies of GTAW butt joints of structural MA2-1M magnesium alloy showed that the weld metal has a dendritic structure (Figure 4). Columnar dendrites directed away from the fusion line into the weld metal are observed in it near the line of weld fusion with the base material. Recrystallization of base metal grains occurred in the HAZ. Directly next to the fusion line the grains are partially melted.

Specimens of GTA welded joints with weld reinforcement have the tensile strength of 267 MPa, which is equal to 96 % of this value for base metal. Their fail from the weld face side in the zone of weld fusion with the base material, and from the root side — in the base metal in the HAZ at approximately 5 mm distance from the line of weld fusion with the base material (Figure 5). Specimens with root penetration cut off flush with the base material and with addition-

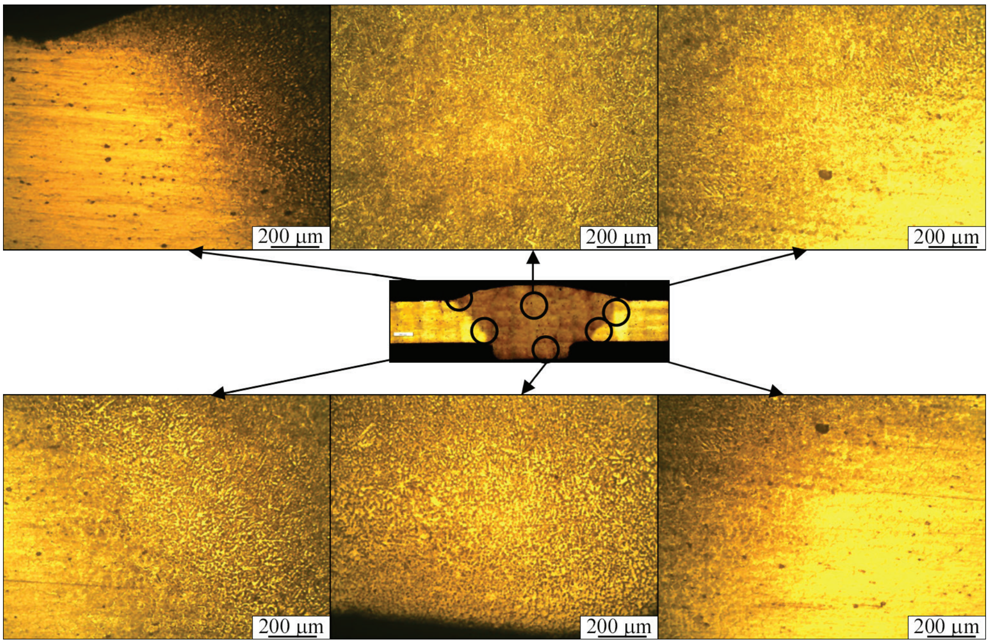

Figure 4. Fragments of the microstructure of GTA welded butt joint of 2 mm structural MA2-1M magnesium alloy

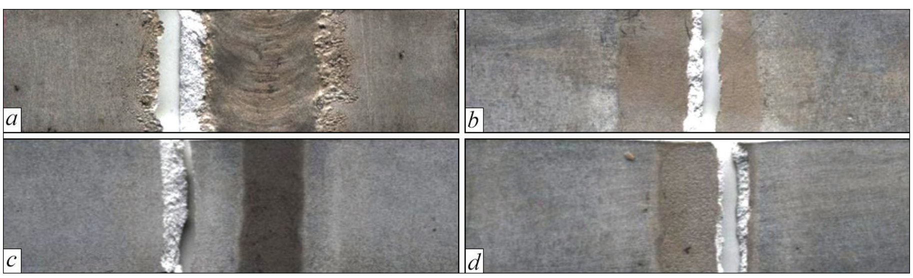

Figure 5. Appearance of the face (*a*, *c*) and root (*b*, *c*) surfaces of the working part of GTA welded specimens of 2 mm MA2-1M magnesium alloy with weld reinforcement (*a*, *b*) and without it (*c*, *d*)

ally scraped weld reinforcement failed at static tension in the weld metal and their ultimate strength was at the level of 233 MPa, which is confirmed by minimal hardness in the weld central part (Figure 6). Accordingly, specimen fracture from the weld face side occurred near its central part, and from the root side it ran in the zone of weld fusion with base material.

CONCLUSIONS

1. Microhardness of FS welded joint is minimal in the zone of thermomechanical impact from the retreating side near (2.5–3.0 mm) the HAZ, which is exactly the region where such specimens fail at their static tension.

2. The structure of GTA weld metal is dendritic. Columnar dendrites directed away from the fusion line into the weld metal are found in it near the zone of weld fusion with base material. Minimal hardness is observed in the weld center. In friction stir welding of this alloy intensive plastic deformation of the metal in the weld central part (nugget) results in formation of grains 5 times finer than the base metal structure. In the thermomechanical impact zone a complete reorientation of the grains in the direction of movement of the tool working surfaces takes place. It results in formation of extended elongated grains oriented along this trajectory.

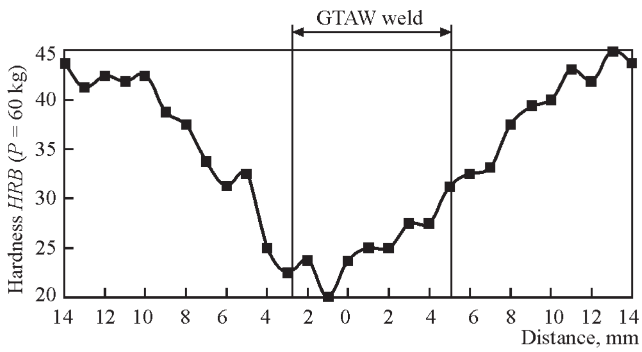

Figure 6. Hardness of metal of GTA welded joint of 2 mm MA2-1M alloy

3. GTA welded specimens with weld reinforcement have the maximal tensile strength (267 MPa), which is equal to 96 % of this value for base material. Tensile strength of FS welded joints, as that of specimens with root penetration cut off flush with base material and with additionally scraped weld reinforcement of welds made by the fusion process, is at the level of 233–236 MPa.

REFERENCES

1. Zuemer, N. (1998) Magnesium alloys in new aeronautic equipment. In: *Proc. of the Conf. on Magnesium Alloys and their Applications*, Wolfsburg, Germany, 125–132.
2. Luo, A.A. (2002) Magnesium: Current and potential automotive applications. *JOM*, February, 42–48.
3. Shapiro, A.E. (2005) Brazing magnesium alloys and magnesium matrix composites. *Welding J.*, **10**, 33–43.
4. Avedesian, M.M., Baker, H. (1999) *Magnesium and magnesium alloys, metals*: Handbook. Materials Park. Ohio, ASM Int.
5. Sachin, K., Chuansong, W. (2017) Review: Mg and its a loy — scope, future perspectives and recent advancements in welding and processing. *J. of Harbin Institute of Technology (New Series)*, 24(**6**), 1–37. Doi: 10.11916/j.issn.1005-9113.17065.
6. Hongjie, L., Jis, M., Wencai, L. et al. (2022) Influence of TIG welding process parameters on microstructure and mechanical properties of as-cast Mg–8Li–3Al–2Zn–0.5Y alloy. *J. of Materials Research and Technology*, **20**, 4114–4129. DOI: https://doi.org/10.1016/j.jmrt.2022.08.157
7. Thomas, W.M., Nicholas, E.D., Needham, J.C. et al. (1991) *Friction stir butt welding*. Int. Pat. Appl. No. PCT/GB 92/02203; GB Patent Applications No. 9125978.8.
8. Defalco, J. (2006) Friction stir welding vs. fusion welding. *Welding J.*, **3**, 42–44.
9. Lee, W.B., Leon Y.M., Jung, S.B. (2003) Joint properties of friction stir welded AZ31B–H24 magnesium alloy. *Mater. Sci. and Technol.*, **6**, 785–790.
10. Aritoshi, M. (2005) Friction stir welding of magnesium alloys sheets. *J. of the Japan Welding Society*, **3**, 18–23.
11. Poklyatsky, A.G., Grinyuk, A.A. (2001) Effect of parameters of asymmetric and modulated currents on quality of aluminium alloy welded joints. *The Paton Welding J.*, **7**, 33–36.
12. Ishchenko, A.Ya., Poklyatskyi, A.G. (2020) *Tool for friction stir welding of aluminium alloys.* Pat. 54096 Ukraine, Int. Cl. B23K 20/12; PWI, No. u201005315, Fill. 30.04.2010, Publ. 25.10.2010 [in Ukrainian).
13. Poklyatskii, A.G. (2019) Prediction of parameters of friction stir welding of sheet aluminium alloys. *The Paton Welding J.*, **8**, 37–42. DOI: https://doi.org/10.15407/tpwj2019.08.06

ORCID

V.E. Fedorchuk: 0000-0002-9929-3231,
S.I. Motrunich: 0000-0002-8841-8609,
Yu.V. Falchenko: 0000-0002-3028-2964

CONFLICT OF INTEREST

The Authors declare no conflict of interest

CORRESPONDING AUTHOR

A.G. Poklyatskyi
E.O. Paton Electric Welding Institute of the NASU
11 Kazymyr Malevych Str., 03150, Kyiv, Ukraine.
E-mail: pag556a@gmail.com

SUGGESTED CITATION

A.G. Poklyatskyi, V.E. Fedorchuk, S.I. Motrunich, Yu.V. Falchenko, M. Sahul (2024) Strength and structure of MA2-1M magnesium alloy butt joints produced by argon-arc welding with a non-consumable electrode and by friction stir welding. *The Paton Welding J*., **2**, 14–18.

JOURNAL HOME PAGE

https://patonpublishinghouse.com/eng/journals/tpwj

Received: 22.09.2023
Received in revised form: 27.11.2023
Accepted: 29.01.2024