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Improving the Formation and Quality of Weld Joints on Aluminium Alloys during TIG Welding Using Flux Backing Tape

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Abstract: This work aimed to compare the quality and properties of the welded joints of AMg6 aluminium alloy produced via conventional TIG welding with the properties of those produced with flux backing tape. This study focussed on the relative length of oxide inclusions (Δ_{oi}) and the amount of the excess root penetration (h_{root}) of the AMg6 alloy weld beads. The results show the influence of the thickness of the flux layer of the backing tape on the formation and quality on the AMg6 alloy welds, along with the effect of flux backing tape and edge preparation on the mechanical properties of the 6 and 8 mm thick welded plates. In accordance with the results obtained, the joints produced by means of TIG welding with flux back backing tape and without edge preparation have higher mechanical properties. Moreover, the TIG welding of AMg6 alloy using flux backing tape reduces the total welding time by 55%, reduces filler wire consumption by 35%, reduces shielding gas consumption by 43% and electricity consumption by 60% per 1 linear meter of the weld line.

Keywords: TIG welding; aluminium alloy AMg6; flux backing tape; X-ray test

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1. Introduction

Aluminium alloys are characterized by a combination of properties widely required in the industry, such as being lightweight, very strong, and very malleable, as well as having excellent wear resistance and good thermal and electrical conductivity and mechanical properties at room temperature [1–3].

Owing to their high strength-to-weight ratios, corrosion resistance and high machinability materials, aluminium alloys, especially 5xxx and 6xxx, are employed in marine construction and shipbuilding [4]. Aluminium alloys are widely used in the fields of electronic technology and automotive body structures. The mass of vehicles has been steadily reduced over the years to reduce fuel consumption and pollutant emissions. The mass of an average diesel car sold in 2017 was 20 kg lower than in 2016 [5].

Aluminium alloys, especially 7xxx and the second and third generation of 2xxx, are very effective structural materials for aerospace applications [6,7]. Welding is the most widely used joining process in industrial applications. Tungsten inert gas (TIG), metal inert gas (MIG), friction stir welding (FSW), laser beam welding and electron beam (EB) welding techniques are mostly preferred for the joining of aluminium alloys [8–13]. The TIG welding process suffers from a lack of penetration in a single pass, leading to poor productivity [14–19]. Moreover, rapid oxide formation and susceptibility to issues such as porosity and cracking present challenges for conventional fusion welding techniques, particularly for light materials such as aluminium and magnesium alloys. These shortcomings constitute the main concerns regarding this process for the fabrication of light material plates. To overcome these problems, the ATIG technique was introduced, which is a variant of the conventional TIG welding. ATIG was first introduced in the mid-1960s by E.O. Paton Electric Welding Institute, Ukraine. ATIG welding methodology was approved by the British Institute of Welding in the 1990s, which confirmed the applicability of this process. In ATIG welding, the same equipment is used as in TIG welding, except that prior to welding a thin layer is deposited on the top edges of plate, which are joined using a brush [20,21]. The main constituents of the flux are oxides and halides in a fine powdered form [22]. Also, the flux can be deposited on the workpiece by spraying with atomized powder using cans or conveyed with a shield gas. Active flux is a chemical purifying, flowing, or cleaning agent. Flux is primarily used to absorb impurities from slag and remove oxide impurities from welds [23–27]. The main mechanisms occurring to enhance the depth penetration are reverse Marangoni convection [28,29] and arc constriction [30–32]. The first mechanism involves the reversal of Marangoni convection. With the presence of surfactant elements such as oxygen, sulphur, selenium and tellurium, the surface tension of the liquid just under the arc weld will be greater than that at the edges. Consequently, the molten metal will move from the edges to the centre of the weld pool, resulting in a deep weld bead. The second mechanism is arc constriction, in which elements such as fluorine contained in the flux migrate to the arc and react with outer arc weld electrons. The arc is constricted, resulting in the density of the energy provided to the weld pool being enhanced. The exothermic flux effect increases the temperature of the welding arc [33,34]. The predominance of the above cited mechanisms depends on many factors, such the chemical composition, the thermophysical properties of the flux, the welding mode conditions and the parameters [35].

Marine usages for Al–Mg alloys are mostly divided into the construction of ship frames and arming. The aluminium materials used by each shipyard differ according to the ship design and the task requirements. ASTM B928 standards [36] state that the 5086, 5083, 5383, 5456, and 5059 Al–Mg alloys and H116 and H321 Al–Mg tempers are recommended for marine service [37]. The 5xxx series Al–Mg alloy is known to be lightweight, easy to machine, and high in strength, along with other attributes. Since the 1950s, large amounts of the alloy have been used in the structures of ships due to its excellent corrosion resistance when immersed in seawater [38,39].

The AA 5xxx is a Mg-based alloy which has excellent characteristics with a high fatigue strength and good corrosion resistance, facilitating its use in marine applications. However, many studies have reported that aluminium alloys are subjected to premature failure under the combined action of stress and a corrosive environment. Several investigations have been dedicated to avoiding this shortcoming through surface modifications and thermomechanical treatments [40]. In other hand, high susceptibility to intergranular corrosion and stress corrosion cracking is a harmful feature of the 5xxx series Al alloys with a high Mg content (>3 wt%), owing to the precipitation of the electrochemically active Mg-rich β phase at grain boundaries [41]. Moreover, welding residual stress has also been reported to be a causal factor in the fatigue cracking of steel bridges [42].

Unfortunately, plates with a thickness of no more than 3 mm can be welded in a single pass with the available welding techniques used in shipbuilding [43–47]. Usually, for plates with a thickness of more than 3 mm consisting of products made from aluminium alloys, several passes are required (two or more) to achieve fully penetrated welds. Moreover, edge preparation is necessary before welding, such as V-, Y-, and X-groove welds for butt welding, depending on the thickness of the welded metal. In order to obtain a high-quality weld, an increase in the filler metal in the weld bead is required. However, this contributes to an increase in the number of defects in the weld in the form of pores and oxide inclusions.

In addition, during unsupported welding, which is typical for welded products and structures for which it is impossible to use bulky forming supports, there is poor formation of the root of weld, with a large penetration bead thickness and a sharp transition from the melted metal to the main one. This leads to a degradation of operational characteristics, especially under dynamic loads.

An effective way to overcome the above shortcomings occurring during conventional TIG welding is the use of weld-shaping and scouring fluxes and flux backing tape. Flux applied to the back side prevents the weld penetration from sagging when welding products up to 4 mm thick. However, when welding of the plates with a thickness of greater than 4 mm, the flux cannot keep the weld penetration from sagging. Therefore, for plates with a thickness of more than 4 mm, flexible tape is used together with the flux. The tape prevents the weld bead from sagging. Moreover, the flux cleans the weld metal of oxide films and removes porosity, while also protecting the weld penetration from the external environment [48,49]. Weld-shaping and scouring fluxes are used during the welding of plates with a thickness of up to 5 mm, but for plates with a thickness beyond this limit, it is recommended that flux backing tape is used. The flux backing tape is attached to the back surface edges of the plates to be joined.

Backing plate support is a technique used when sagging can occur. The use of the backing material aims to support the molten metal of the weld pool and prevent the collapse of the weld pool. Temporary backing materials are usually used when the backing material is different from the base material and it does not fuse with the base metal. Backing materials can be metallic or non-metallic, such as ceramics, composites, asbestos, and fiberglass. It has been reported that during welding, the backing medium changes the weld temperature in the workpiece, and in turn influences the mechanical properties of the welded plate [50]. Singh et al. [51] noted that cast-iron plates that were used as a backing medium helped full penetration to be achieved in a 6 mm thick P91 plate when three backing media were used, namely cast-iron, copper, and mild steel plates.

The novelty of this work is the use of flux backing tape. This new technique prevents excess penetration (root excess penetration) and the collapse of weld pool. Secondly, it contributes to a significant reduction in the number of defects in comparison to the conventional TIG process. Finally, it protects the weld molten metal from the surrounding environment and related contaminants. The purpose of this work was to study the effect of using flux backing tape in TIG welding of the AMg6 Al-Mg alloy (5xxx series) on the quality and mechanical properties of welded joints.

2. Materials and Methods

The aluminium–magnesium alloy AMg6 is widely used in shipbuilding and construction in Eastern Europe. The AMg6 alloy is equivalent and close to the brand AA5056. The feed wire, according to the GOST 14838-78 standards [52], has a 1.2 mm diameter. The chemical composition of AMg6 alloy and feed wire are shown in Tables 1 and 2, respectively.

Table 1. Chemical composition of the aluminium alloy AMg6 (in weight %).

Alloy	Cu	Mg	Mn	Zn	Fe	Si	Ti	Be
AMg6	0.1	5.8–6.8	0.5–0.8	0.2	0.4	0.4	0.02–0.1	0.0002–0.005

Table 2. Chemical composition of AMg6 feed wire (according to the GOST 14838-78 standards).

Elements	Mg	Mn	Zr	Ti	Al
Weight %	5.50–6.20	0.80–0.90	0.08–0.12	0.02–0.2	balance

The preparation of welded plates for TIG welding according to conventional technology was carried out with a Y-groove butt weld joint, as depicted in Figure 1a, and using flux backing tape without edge preparation for butt welding, as shown in Figure 1b.

The flux backing tape was obtained by applying a 10 mm wide and 0.2–0.4 mm thick layer of flux on the surface of a flexible and thin fiberglass backing tape, which was attached to the welded plates on the root side via an adhesive tape. Flux belonging to the TFA-4 brand [48] was used in the form of paste applied to the backing tape.

(**a**) (**b**)

Figure 1. Schemes of edge preparation for butt welding: (**a**) for welding according to conventional technology; (**b**) for welding using flux backing tape.

The thickness of the flux layer was measured using the micrometric method. This method allows the measurement of the thickness of the flux layer using measuring instruments with a measurement error limit of 5 microns. In this method, the thickness of the flux layer was determined by taking at least three measurements of the thickness of the backing tape without flux and with flux using an digital micro meter tool. The thickness of the flux layer was determined by the difference in the readings.

The welding parameters of the automatic TIG welding of the aluminium alloy AMg6 using conventional technology in two passes and with the use of flux backing tape in one pass are shown in Tables 3 and 4, respectively.

Table 3. Parameters of the automatic TIG welding without flux backing tape in two passes with a Y-groove butt weld joint edge preparation.

Thickness (mm)	Welding Pass	Welding Currents (A)	Arc Voltage (V)	Welding Speed (cm/min)	Feed Wire Speed (cm/min)	Shielding Gas Rate (L/min)	Heat Input (kJ/cm)
6.0	First	140–150	11–12	25	-	8–10	3.960–4.032
	Second	220–230	16–17	25	110–120	9–11	8.832–8.976
8.0	First	160–170	13–14	25	-	8–10	5.304–5.376
	Second	260–270	18–19	25	110–120	9–11	11.664–11.856

Table 4. Parameters of the automatic TIG welding using flux backing tape in one pass for a butt weld joint without edge preparation.

Thickness (mm)	Welding Currents (A)	Arc Voltage (V)	Welding Speed (cm/min)	Feed Wire Speed (cm/min)	Shielding Gas Rate (L/min)	Heat Input (kJ/cm)
6.0	270–280	19–20	25	70–80	9–11	12.768–12.960
8.0	320–330	21–22	25	70–80	10–12	16.632–16.896

After welding, the samples were cut far enough away from the welding starting point to be sure that the arc welding was stabilized, as shown in Figure 2.

The tensile tests were performed with a computerized universal testing machine at a tensile rate of 2 mm/min. The samples were prepared in accordance with ASTM E8M-04 [53], and the bending tests were carried out according to ASTM E190-14 standards [54], as shown in Figures 3 and 4, respectively. The tests were carried out on 3 samples with thicknesses of 6 mm and 8 mm, even for TIG and ATIG welds.

The morphology of the welds was revealed using an immersion method in a solution composed of 190 mL of H_2O, 5 mL of HNO_3 (65%), 3 mL of HCl (32%) and 2 mL of HF (40%). X-ray inspection was conducted to reveal the presence of inclusions and pores in the welds. A portable X-ray machine was used for this purpose. We note that the X-ray test was conducted throughout the plate joint according to the ASTM E155-20 specifications [55].

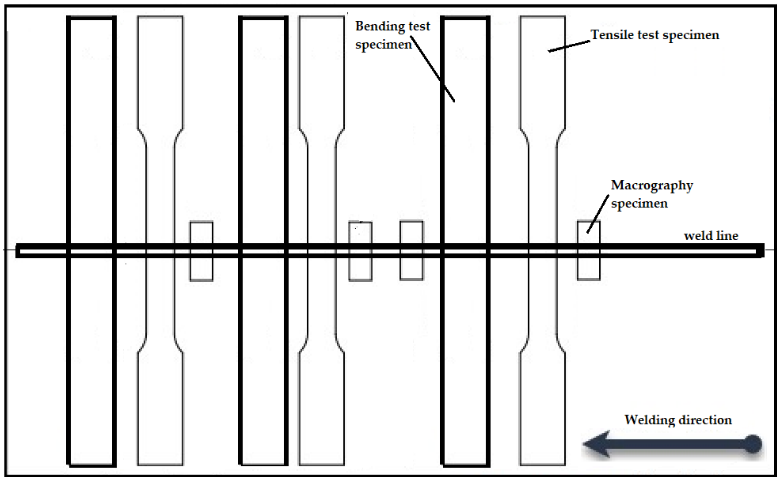


Figure 2. Zones of the test specimens taken for various mechanical and metallographically investigations.

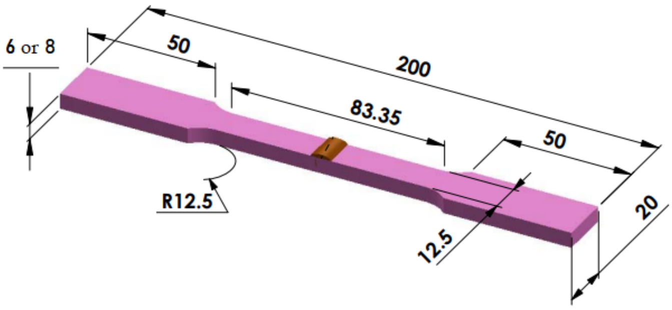


Figure 3. Tensile test specimens according to ASTM E8M-04 (dimensions in mm).

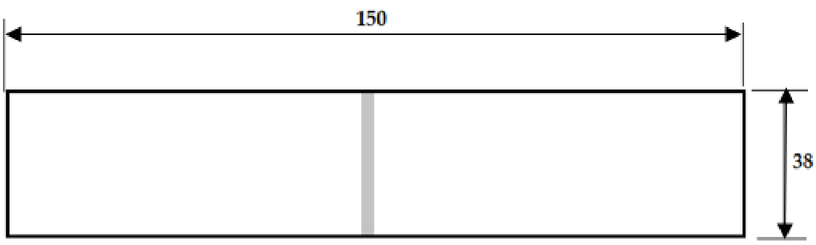


Figure 4. Transverse bend test specimen according to ASTM E190-14 (dimensions in mm).

The clogging of the weld beads with oxide inclusions was estimated according to the magnitude of the relative extent of the oxide inclusions ($\Delta_{o.i}$), which was determined by the ratio of the sum of oxide inclusions in the weld bead ($\sum l_{o.i}$) to the total length of the weld bead (l_{bead}) (see Figure 5):

$$\Delta_{oi} = \sum l_{oi} / l_{bead} \tag{1}$$

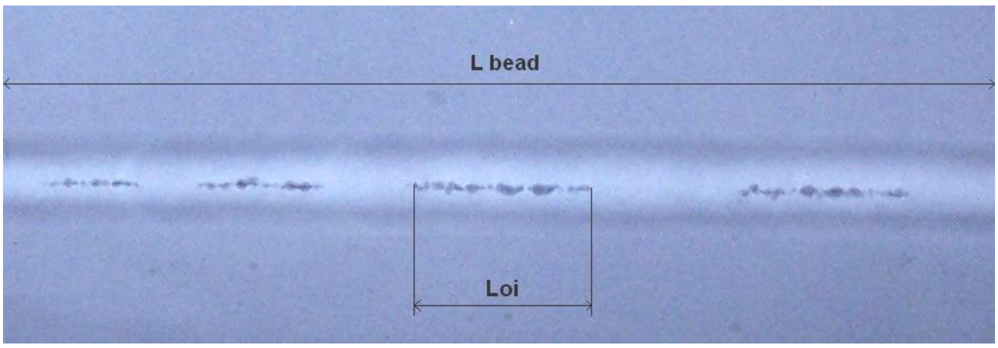


Figure 5. The X-ray test image.

Also, the influence of the use of flux backing tape on the amount of excess root penetration (h_{root}) was assessed (see Figure 6).

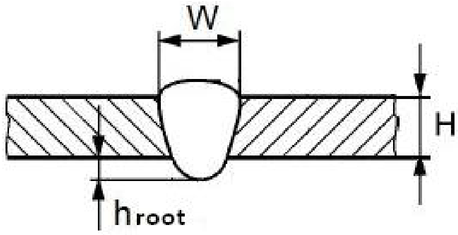
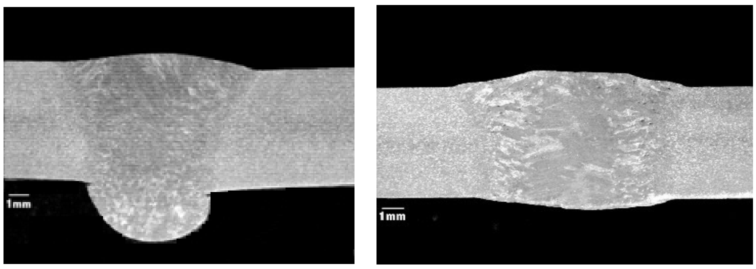


Figure 6. The scheme of the weld bead (W is the width of the weld bead, H is the thickness of the welded metal, and h_{root} is the excess root penetration).

The excess root penetration is a benchmark to judge the soundness of weld beads, i.e., a smooth transition from the melted metal to the base metal enhances the mechanical characteristics of welded joints, especially under dynamic loads. The lower the value of the excess root penetration, the smoother the transition from the melted metal to the base metal, the better the quality of the welds. A smooth transition from the root of the weld bead to the base metal is an industry requirement for welded products, especially those operating under dynamic loads.

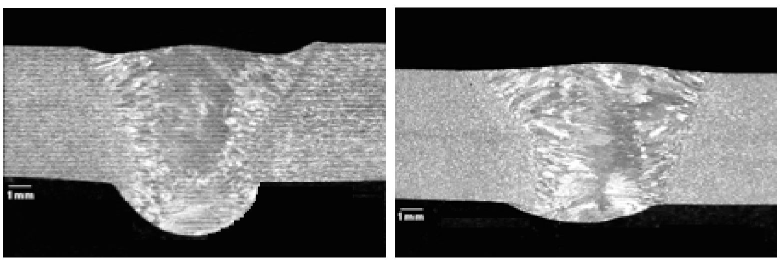
3. Results and Discussions

Figures 7 and 8 show the cross sections of welded joints for plates with thicknesses of 6 and 8 mm, respectively, according to conventional technology (see Figures 7a and 8a) and using flux backing tape (see Figures 7b and 8b) with a butt joint design with and without edge preparation.



(**a**) (**b**)

Figure 7. Cross sections of the AMg6 weld beads (thickness, 6 mm) produced using conventional technology and edge preparation (**a**) and using flux backing tape without edge preparation (**b**).



(**a**) (**b**)

Figure 8. Cross sections of the AMg6 weld beads (thickness, 8 mm) produced using conventional technology and edge preparation (**a**) and using flux backing tape without edge preparation (**b**).

Figure 9 shows the beneficial effect of the flux backing tape on the external aspect of the back side of the weld. The weld bead produced with flux backing tape is clean and shiny. During this study, the influence of flux backing tape and the thickness of the paste flux on the formation and quality of the AMg6 alloy weld was examined. Figure 10 shows the dependence of the relative length of oxide inclusions (Δ_{oi}) in the AMg6 welds on the thickness of the flux (s) applied to the backing tape. According to the results obtained, the weld beads on the AMg6 alloy are most effectively cleaned of oxide inclusions with a thickness of the applied flux in the range of 0.3–0.4 mm. When the thickness of the flux is less than 0.3 mm, the length of the oxide inclusions is reduced, but the amount of applied flux is insufficient to completely remove these inclusions. In the case applying of this flux with a thickness of more than 0,4 mm, the quality of the welded joints is reduced due to the formation of a large amount of gaseous emissions resulting from the evaporation of the flux components between the liquid metal of the welding bath and the backing tape.

Figure 9. The effect of the flux backing tape on the back side of the welds.

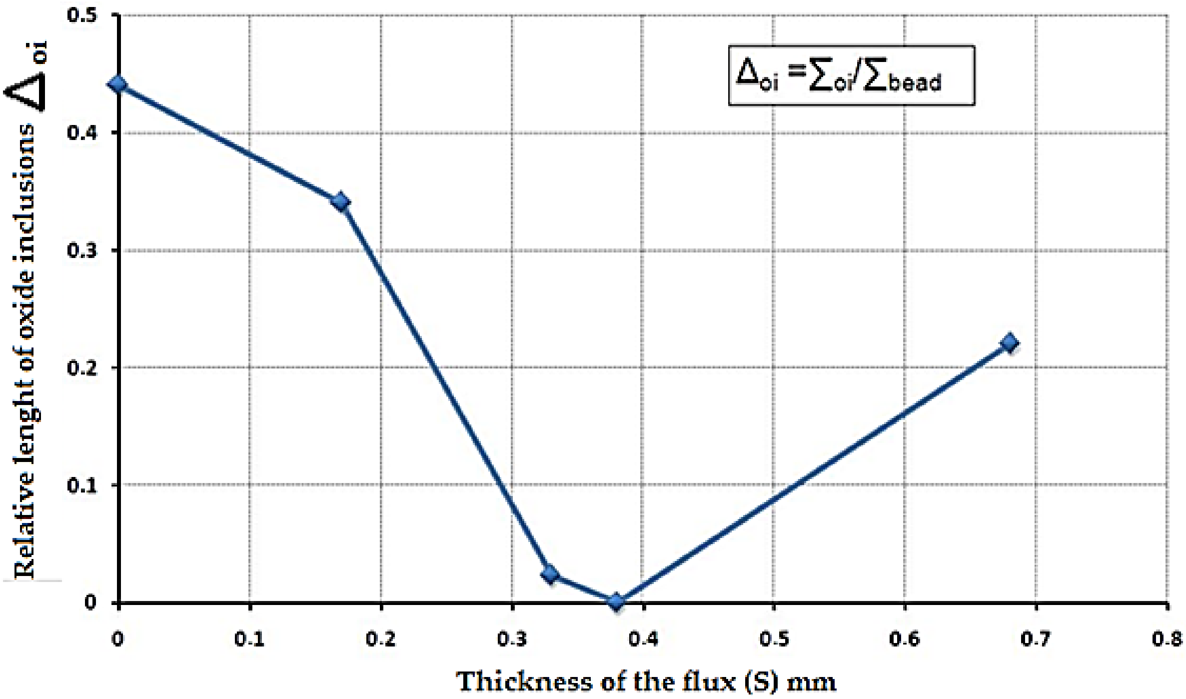


Figure 10. The dependence of the relative length of oxide inclusions (Δ_{oi}) in the weld beads on AMg6 alloy on the thickness of the flux (S) applied to the backing tape.

The influence of using flux backing tape and the thickness of the flux on the amount of excess root penetration (h_{root}) is shown in Figure 11. The results obtained show a decrease in the excess root penetration compared with welding without a support by almost ten times. The thickness of the flux applied to the backing tape has almost no effect on the amount of sagging.

Figure 12 shows the effect of four variants of the TIG welding method on the relative length of oxide inclusions (Δ_{oi}) and the amount of weld root penetration (h_{root}). In accordance with the results obtained, the use of conventional backing tape as a support during welding effectively reduces excess root penetration by ten times, but contributes to an increase in oxide inclusions in the weld bead metal. Using a flux paste applied to the back side solely allows one to completely clean the weld metal from oxide inclusions; however, it does not effectively reduce root penetration. The best result was achieved by using flux backing tape; oxide inclusions were successfully cleaned and completely removed and a sharp reduction in root penetration was observed.

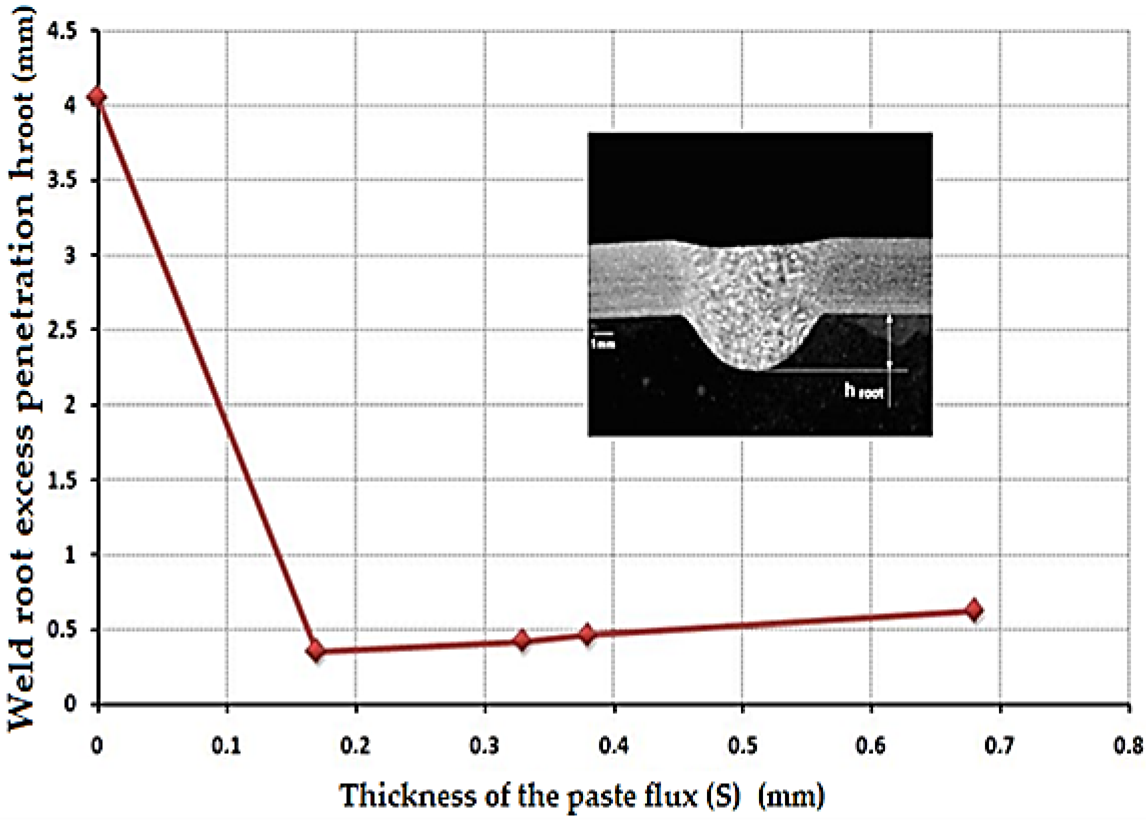


Figure 11. Dependence of the amount of the penetration of the weld bead on the AMg6 alloy on the thickness of the flux (S) applied to the backing tape.

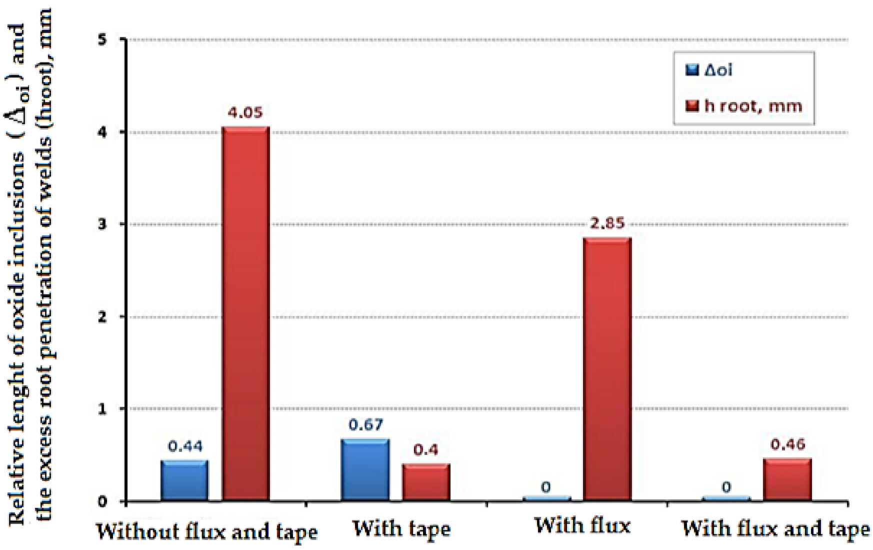


Figure 12. Comparative results on the relative length of oxide inclusions (Δ_{oi}) and the amount of bead penetration (h_{root}) on the AMg6 alloy obtained by means of various TIG welding methods.

We noticed that welds produced with a Y-groove edge preparation have numerous defects compared to those obtained without edge preparation. The presence of a large number of defects is associated with the migration of oxide inclusions and moisture from the filler metal inside the liquid metal in the weld pool. Apparently, this effect is due to the high contribution of filler metal in the case of plates with a Y-groove edge preparation. In fact, the plates with edge preparation require more filler metal to fill the volume between plates in comparison to the space between plates without edge preparation. With edge preparation, the increase in the number of oxide inclusions and pores in the weld metal degrades the mechanical properties of the obtained joints. Therefore, using flux backing tape is more efficient during welding without edge preparation of the welded plates. The obtained results of the mechanical tests of AMg6 alloy welded joints using conventional backing tape support and flux backing tape for edge preparation and without edge preparation are depicted in Table 5. The weld beads produced using flux backing tape without edge preparation have superior strength properties. This result is ascribed to the effective removal of oxide inclusions and pores from the weld pool during TIG welding using flux backing tape. On the other hand, a small amount of filler metal was introduced to this variant of the TIG weld bead. The results displayed in Table 4 are the average values of three tensile and bending tests. We noted that for a thickness of 6 mm, the tensile strength on the AMg6 alloy was 297 MPa, while for a thickness of 8 mm, it was 315 MPa, according the certificate specification received from supplier.

Table 5. Mechanical properties of 6 and 8 mm thick TIG and ATIG AMg6 welded joints produced with and without edge preparation.

Thickness (mm)	Welding Method	Preparation of the Welding Edges	Weld Tensile Strength σ_B, MPa	σ_B/σ_{Bm} Ratio	Bending Angle, °
6.0	With backing tape	Without edge preparation	179	0.6	50
	With flux backing tape		271	0.91	82
	With backing tape	With Y-groove edge preparation	225	0.75	101
	With flux backing tape		236	0.79	97
8.0	With backing tape	Without edge preparation	178	0.56	89
	With flux backing tape		265	0.84	83
	With backing tape	With Y-groove edge preparation	233	0.74	-
	With flux backing tape		236	0.75	-

In accordance with the bending results of welded joints (see Table 5), it can be seen that the effects are ambiguous, i.e., it is difficult to unambiguously judge the positive effect of using flux backing tape on the bending angle of a welded joint. This is due to the presence of defects (pores and oxide inclusions) in the beads. Considering that when preparing samples of welded joints for bending, the excess root penetration of the beads, in which defects are mainly located, is removed, the bending angle can be high even without the use of flux backing tape during welding.

We noticed that using flux backing tape during the TIG welding of aluminium AMg6 alloy with a thickness of 6 mm can reduce the total welding time by 55%, the consumption of filler wire by 35%, the consumption of shielding gas by 43% and electricity consumption by 60% per 1 m length of the weld bead, making this technique very interesting for various industries.

4. Conclusions

The aim of this study is to propose a flux backing technique to join AMg6 alloy in a butt join design. This work is a comparison study between conventional AMg6 alloy TIG welds and welds produced using flux backing tape during TIG welding. The following main conclusions can be drawn:

➢ Flux backing tape during TIG welding allows full-penetration welds with a thickness of up to 8 mm to be achieved in a single pass without any edge preparation. The quality and mechanical properties of the welded joints were significantly enhanced.

The proposed technique increases productivity and reduces the complexity of welding work, as well as economizing the use of welding materials and electricity.

- ➢ The quality of the welded joints produced using flux backing tape is higher in comparison with those obtained using the conventional TIG process. The obtained results showed a decrease in root penetration compared with welding without flux backing tape, by several times.
- ➢ It is established that the using flux backing tape during TIG welding on the AMg6 alloy contributes to the removal of oxide inclusions. The flux backing tape's effectiveness is more obvious when the thickness of the flux on the backing tape is in the range of 0.3–0.4 mm.
- ➢ The proposed variant of the TIG welding method, in comparison with the conventional TIG process, enable an increase in productivity. The flux backing tape technique reduces the complexity of welded products by two times and decreases the cost of welding materials by up to 43% and electricity consumption by up to 60%, meeting the industry's needs.
- ➢ The flux backing tape technique is more effective in joining aluminium alloy AMg6 plates with thicknesses of more than 4 mm in comparison with TIG welding performed with a ceramic support. A flexible tape is used together with the flux. The tape prevents the weld bead from sagging. Moreover, the flux cleans the weld metal of oxide films and removes porosity, and also protects the weld penetration from the external environment.

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