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Comparison between microstructure characteristics and joint performance of AZ31 magnesium alloy welded by TIG and friction stir welding (FSW) processes

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Abstract

This study aims at researching mechanical properties of TIG welding which has been used for magnesium welding and friction stir welding; this is a new method for magnesium welding. It particularly focuses on analysing of bending fatigue test among other mechanical properties. Joints made through TIG and FSW welding for magnesium applications in automotive and aeronautical-astronautical industries are exposed to various mechanical stresses and in particular to dynamic loads when vehicles are in motion. Fracture has been observed in welding areas due to such dynamic loads. This analysis mainly concentrates on the differences between these two welding methods: TIG and FSW welding, and on determining the method with superior advantages due to the fact that TIG welding has been intensely used for magnesium welding, and friction stir welding is a new application in terms of magnesium welding.

Key words: magnesium (Mg) alloy, friction stir welding, TIG welding, bending fatigue strength

1. Introduction

Magnesium, with its lightness and strength, is a very commonly used metal in industry. Magnesium is the lightest of all the engineering metals, having a density of $1.74\,\mathrm{g\,cm^{-3}}$. It is 35 % lighter than aluminium ($2.7\,\mathrm{g\,cm^{-3}}$) and over four times lighter than steel ($7.86\,\mathrm{g\,cm^{-3}}$) [1]. This indicates its potential in aeronautical/astronautical applications, for which weight saving is of vital importance. Imagining that weight saving in the same amount achieves a certain amount of financial saving in automotive industry, this amount is 100 times more in a commercial aircraft, 1000 times more in fighter aircraft and 10000 times more in an astronautical application [2].

Tendency for light metallic materials, particularly in automotive industry, is not only relevant to automobiles of today. Lightness for future automobiles prescribed to run on alternative energy sources such as solar energy, electricity or hydrogen, is more important requirement compared to today's automobiles. Fuel consumption planned to be achieved for personal autos in the upcoming years is a difficult target of 3 l/100 km and this requires a 30 % reduction in automobile weight. While magnesium has an edge over plastics with its recyclability, it may compete against aluminium in terms of pressure die casting applications for automotive industry requiring manufacturing with a higher speed casting. Less harmful gas emission means less fuel consumption; less fuel consumption means less weight and less weight means lighter materials. The best way to decrease vehicle weight is to benefit from low density materials [3–15].

The usage area of magnesium, the youngest metal of our century, has been extending and its importance has been increasing in parallel with progress in industry and technology in order to satisfy the requirements of human beings. Magnesium and its alloys have been primarily favoured for lighter, stronger, more efficient, more durable, and therefore more economic products. There has been advancement in welding techniques in parallel with progress in magnesium.

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Table 1. Chemical properties of used metal AZ31D (wt.%)

	Mg	Al	Zn	Mn	Si <	Fe	Cu <	Ni <	CA	Others
AZ31D	94–96	2.5–3.5	0.6–1.4	0.2–1.0	0.05	0.002	0.01	0.001	0.04	0.01

Table 2. Mechanical properties of used metal AZ31D

	Yield strength (MPa)	Tensile strength (MPa)	Elongation (%)	Hardness HB
AZ31D	182	213	3.97	51.3

It is difficult to weld magnesium plates by means of welding techniques of fusion welding. It is not possible to obtain required mechanical characteristics after the welding process [4, 15–20].

While some difficulties may be experienced during welding magnesium and its alloys with fusion welding methods, such methods are not used for welding some of these alloys. A material's ability to be welded is an important property which ensures it to be more commonly used and which has a role in determining the part manufacturing method for the material.

The purpose of this research is to compare mechanical properties of 4 mm thick AZ31D sheets welded by using TIG and FSW processes.

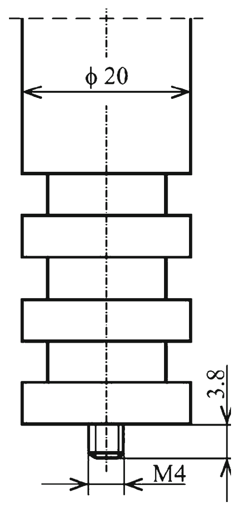

Fig. 1. Dimensions of the tool used for FSW (in mm).

2. Experimental method and materials

2.1. Base material

In this research, 4 mm thick magnesium alloy (AZ31D) sheets were welded with FSW and TIG welding methods. Chemical and mechanical properties of studied material are shown in Table 1 and Table 2, respectively.

The dimensions of the welded plates were 300 mm (length) × 125 mm (width) × 4 mm (thickness).

2.2. Welding experiment

2.2.1. Application of TIG welding method

Commercial 1.2 mm diameter AZ31D welding electrodes were used in TIG welding process. Butt welding was performed with TIG method.

2.2.2. Friction stir welding (FSW)

FSW tool was manufactured from 2344 hot work steel, which has a melting temperature 3 times higher than aluminium base metal.

The pin profile was formed as M4 with 3.8 mm length shown in Fig. 1.

FSW was performed with the help of semi-automated milling machine. The specimens were tightly fixed. FSW tool was mounted on the vertical shaft of the milling machine, and a tilt angle of 2° degree was used in FSW application.

2.3. Sampling principles

Visual examination was performed in order to detect possible surface errors after welding of test samples. This examination was based on ANSI/AWS D9.1-90 Sheet Metal Welding Code [21]. Samples were extracted in accordance with EN 288-3 [22].

According to the test plan, test samples suitable for EN-288-3 were extracted from welded plates which had passed the visual examination. In order to prevent possible failure, 25 mm away from ends had been cut off.

2.4. Bending fatigue test samples

Fatigue testing samples were prepared according to characteristics of the testing machine for each welding

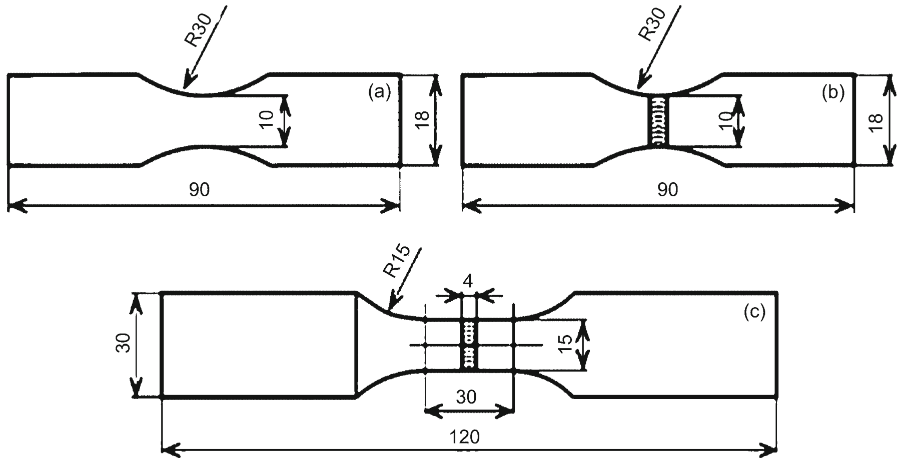

Fig. 2. a) Dimensions of fatigue base metal test specimens, b) dimensions of fatigue welding test specimens, c) tensile test samples.

method and base metal in standard sizes as given in Fig. 2a. Figure 2b shows sample sizes for unwelded base metal, and Fig. 2c shows sample sizes for welded samples. Limit cycle number in all experiments was $N = 2 \times 10^6$ [23].

2.5. Hardness tests

On all samples of welded connections, the hardness test was applied along a line using 500 g of load. When measuring hardness; base metal, heat affected zone and welded metal values were taken by symmetrical distances to the interface of the welded plates.

2.6. Tensile test samples

Tensile test samples were prepared in a similar way the fatigue test samples were prepared. Base metal samples were prepared in accordance with EN 10002--1. TIG and FSW welded samples were prepared in accordance to EN 895, and 3 samples were obtained for each test.

2.7. Visual examination of welded sheets

Visual examination was performed in order to detect possible surface errors after welding test samples. This examination was based on ANSI/AWS D9.1-90 Sheet Metal Welding Code and TIG welded plates were found out to be within acceptable limits. However, some parts which exceeded error limits were discarded.

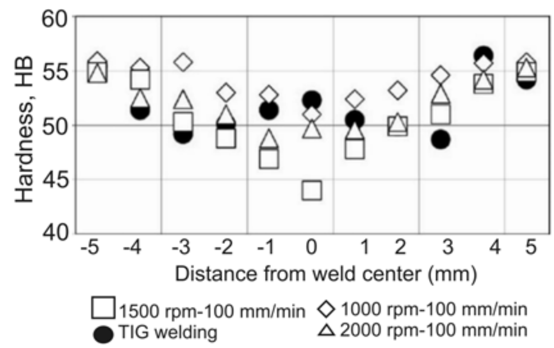

Fig. 3. Hardness values of the samples.

Fig. 4. Fractographs of TIG welded samples after fatigue strength test.

3. Results and discussion

3.1. Hardness tests

Figure 3 shows hardness values of FSW plates with different parameters, and of TIG welded sheets.

3.2. Fatigue tests

Figure 4 shows fracture zones of TIG welded samples after fatigue test. Figure 5 shows fracture zones of FSW samples. Figure 6 shows bending fatigue strength values of the test samples.

3.3. Tensile strength tests

Figure 7 shows tensile strength test results of unwelded base metal, TIG welded samples and FSW samples comparatively in one graph.

Fig. 5. Fractographs of FSWed samples.

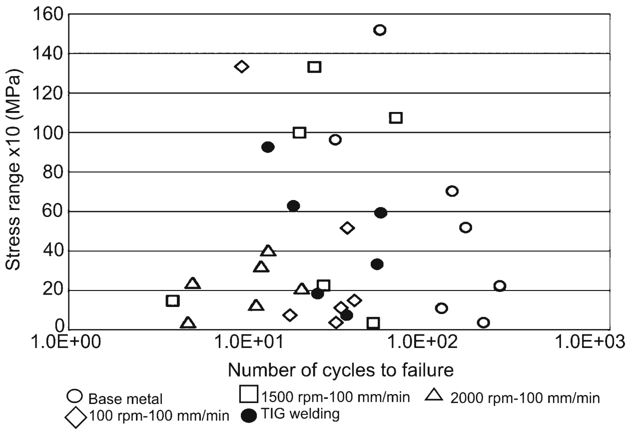

Fig. 6. Bending fatigue strength values of the test samples.

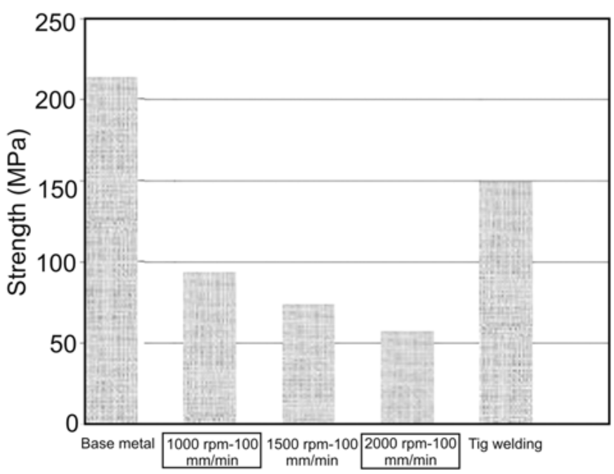

Fig. 7. Tensile strength values of the test samples.

3.4. Visual examination results

Since TIG is a fusion welding method, distortion which occurs because of heat input was normal. Also, various spatters were examined, but since size and distribution values of these spatters are in limits foreseen in international welding procedures (AWS Sheet Metal Code etc.), welded connections are deemed acceptable [24, 25].

Single-sided FSW was performed. The bead of FSW was observed to be compatible with the literature [26]. Surface examination showed that there were no cracks and no unbonded zones in the weld zones. The keyhole defect which welding tool caused at the end of joint was also discarded.

The semi-circular tracks on the surface and root beads caused by welding tool shoulder did not affect the welding strength and FSW method welding beads were deemed normal. Since in FSW, heat input was generated locally, contrary to TIG or other fusion welding methods, there was not any distortion in bonding zones. The results of distortion of FSW plates were consistent with the literature [27–32].

3.5. Hardness calculations

Hardness testing of all welds was performed by 500 g load. Hardness was measured on a line perpendicular to weld bead. Results are shown in Fig. 3.

It is observed in hardness test results that the highest value is 1000 rpm-100 mm min^{-1} while the lowest value is 1500 rpm-100 mm min^{-1}. It is seen that hardness values are usually lower in areas subject to heat effect. In FSW parameters, it is known that heat differences formed on materials during welding in various revolutions not only affect micro-structure and tensile-fatigue strength but also hardness values dependent upon these results. Despite the fact that stirring tip did not have any mechanical effect over the area under the effect of heat, the material was softened since welding was performed dynamically close to the recrystallized area. Increasing revolutions (2000 rpm--100 mm min^{-1}) led to a decrease in hardness value. The reason is that cooling of materials is slower due to increasing heat amount penetrated into the material during high revolutions, which results in decreasing hardness. In Fig. 8, microstructures of FSW and TIG welds are given, respectively.

Heat input over the material is excessive due to high rotation speed and low progression rate. These lead to minimum hardness values [31].

While increasing welding rate enhances orientation of welding metal, however, welding metal orientation is seen more obvious in lower welding rates. Since increasing welding rate will decrease heat input in friction stir welding, hardness level of welding metal changes with increasing welding rate [32].

3.6. Fatigue tests

After fatigue test is applied to prepared samples, fractographs were examined and fatigue crack zones were detected. Fatigue cracks were detected on thin cross-section in base metal samples. Literature research deems this situation as normal [23–35].

From the fracture shape of FSW welded samples after fatigue test, it was observed that fracture occurred on the heat-affected zone, being the weakest

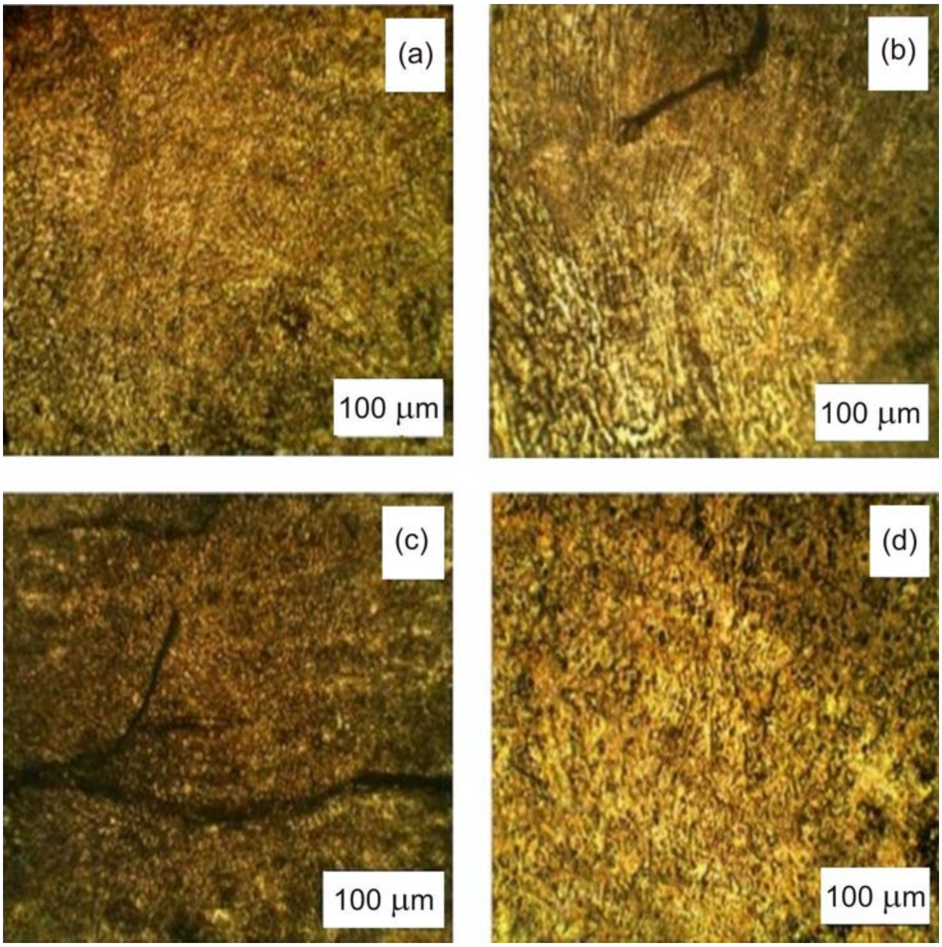

Fig. 8. Microstructures: a) 1000 rpm-100 mm min^{-1}, b) 1500 rpm-100 mm min^{-1}, c) 2000 rpm-100 mm min^{-1}, d) TIG welding.

and most sensitive zone of the joint. This is considered normal and is in accordance with experimental results on this field. Samples that had been broken on beads were excluded [23–35].

Fatigue fraction points of TIG welded samples are very close to and sometimes at the weld metal. The atmospheric gases can diffuse into the welded bead during the welding process, and hence they can affect the welded structure. This decreases the joint strength.

As hardness increases, fatigue strength increases as well; samples of 1000 rpm-100 mm min^{-1} were found to have high fatigue strength. Strength characteristics are negatively affected by high cooling rate which causes strengthening particles to partly precipitate in high speed welding [36].

Also, when materials with high hardness value are used, they are expected to have high fatigue strength [23–36].

In high heat input situations, heat-affected zone of welded joint expands and this causes fatigue strength to decrease.

As seen in diagram in Fig. 6, bending fatigue strength values of base metal are higher than joint samples with any welding method. Fatigue strength values are found to be lower in joint samples with FSW and TIG welding compared to the original material. Results similar to TIG welding in 1000 rpm-100 mm min^{-1} parameter were obtained for all parameters of friction stir welding. When the fact that hardness affects fatigue is considered, this is an expected situation because the lowest hardness values are seen in samples with TIG welding. The highest fatigue strength is obtained from the samples with friction stir welding in 1500 rpm-100 mm min^{-1} parameter. Those test samples have also the highest hardness and tensile strength. This is also an expected situation.

Decreasing fatigue strength is observed due to increasing heat input over the material, extending HAZ (Heat Affected Zone) and decreasing hardness level. The reason is increasing heat input over the material during increasing revolutions rates while the welding progression rate is stable. Strength augmenting particles (copper, aluminium and silicium) in heat affected zone of the welded joint form an inhomogeneous precipitation inside the material [36]. This results in decreasing fatigue strength of the joint. When the welding progression rate is increased together with increasing revolutions rate (1500 rpm-100 mm min^{-1}), it is seen that fatigue strength also enhances. When the revolutions rate is increased, it is possible to decrease heat input over the material through increasing welding progression rate and, therefore, it is possible to control variable parameters such as width of heat affected zone, stirring tip, revolutions rate and welding progression rate.

3.7. Tensile tests

It was observed that fracture occurred at the thermo-mechanically affected zone. Because of deformation of grain structure and welding errors, fractions occur in welding transition zone [25]. This shows stability of welding bead. Tensile strength is affected by notches. As seen in Fig. 7, highest tensile strength values were obtained at the base metal. High value in FSW welded samples is with parameters 1000 rpm-100 mm min^{-1}. It was observed that on FSWed samples, fractions occurred in thermo--mechanically affected zone and compared to fusion welding methods, strength values were higher.

When friction stir welding samples are subject to an evaluation between each other, it is observed that tensile strength decreases with stable progression rates and increasing rotating speed. It is seen that FSW parameters have an impact over tensile strength. When the revolutions rate of stirring tip is increased, precipitation and accumulation in welding seams was found in samples of 2000 rpm-100 mm min^{-1}. As heat input decreases during lower revolutions rates, a more constant and rolled shape is obtained compared to more fragile original material. This shows the existence of a structure homogenized with heat depending upon the most appropriate revolutions and progression rates.

Increasing revolutions rate causes increasing heat input over the material. However, increasing heat leads to precipitation and accumulation alongside the welding seams. This results in thinner welding zone and notch effect over welding seams. Therefore, lower tensile strength values are obtained from the sample of 2000 rpm-100 mm min^{-1}.

4. Conclusions

4 mm thick AZ31D magnesium alloy has successfully been welded using TIG and FSW processes.

1. It was examined that weld bead appearance of FSWed plates was much smoother than that obtained from TIG welding process. No distortion was observed on FSWed sheets because heat input was low as for a solid state process.

2. Fracture was observed to initiate from HAZ and fracture was observed right next to weld bead in bending fatigue tests.

3. Bending fatigue strength of base metal is higher than that of welded samples, similar to tensile strength.

4. With stable welding progression rate and increasing welding revolutions rates, discontinuities, irregularities in the direction of rotation were found leastwise in corrugated image of welding seams due to increasing heat input over the material (2000 rpm-100 mm min^{-1}).

5. Tensile strength values of joint samples with TIG welding are found to be higher than those with friction stir welding.

6. The lowest bending fatigue strength value is found in joint samples with friction stir welding of 2000 rpm-100 mm min^{-1} parameter. Since fatigue strength values of 1000 rpm-100 mm min^{-1} are similar to those of 1500 rpm-100 mm min^{-1}, a progression rate of 1500 rpm-100 mm min^{-1} may be preferred for the machines not able to function in high revolutions rates.

7. For constant travel speed and increasing rotation speed, welded samples showed a decrease in fatigue strength.

Interpreting all data, it can briefly be concluded that FSW process can be controlled by adjusting parameters such as heat input, rotation speed and travel speed. As a solid state welding method, FSW can successfully be applied to aluminium alloy AZ31D, which is difficult to weld with fusion welding methods.

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