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Comparison between mechanical properties and joint performance of AA 2024-O aluminium alloy welded by friction stir welding and TIG processes

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Abstract

In this research, AA 2024-O aluminium material, which is specifically used in aircraft and aerospace industries, was used. Aluminium plates were welded with different methods: tungsten inert gas welding (TIG) is a fusion based process; and friction stir welding (FSW), a solid state process, has held great importance in welding of aluminium and alloys recently. Extracted samples from welded plates were tested for fatigue strength, tensile strength and hardness. The results of experimental studies show that friction stir welded plates provide better on overall basis.

Key words: AA 2024-O aluminium alloy, friction stir welding (FSW), tungsten inert gas (TIG) welding, bending fatigue strength

1. Introduction

Friction stir welding (FSW) is a solid state joining process that was developed by the TWI, UK in 1991 [1]. FSW is a relatively new and promising welding process that can produce low-cost and high-quality joints of heat-treatable aluminium alloys. FSW is well suited for joining aluminium alloys, especially for those usually considered difficult to weld, such as 2xxx and 7xxx series [2–4].

FSW of aluminium alloys has been used in the field of aircraft, shipbuilding, automotive, railway, defence industries, and attracted extensive research interest due to the potential engineering importance. Problems such as reduced strength of the joints, distortions, residual stresses, gas porosities, metallurgical precipitations in the weld metal and heat affected zone (HAZ), lack of fusion, high coefficient of thermal expansion, solidification shrinkage, high solubility of hydrogen and other gases associated with conventional welding are well reduced in FSW [5–13].

The purpose of this research is to compare mechanical properties of 4 mm thick AA 2024-O Al-alloy sheets welded by using TIG and FSW processes, respectively.

Moreover, this research also aims to determine the variations under constant rotation speed and increased travel speed.

2. Experimental method and materials

2.1. Base material

In this research, 4 mm thick aluminium alloy (AA 2024-O) sheets were welded with FSW and TIG welding methods. Chemical and mechanical properties of studied material are shown in Tables 1 and 2.

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

1.2 mm diameter ER4043 (SG-ALSi5) filler metals were used in TIG welding process. Butt welding was performed with TIG method.

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T a b l e 1. Chemical properties of the used metal: AA 2024-0

Fe	Si	Cu	Mn	Mg	Zn	Ti	Cr
0.50	0.50	3.80–4.90	0.30–0.90	1.20–1.80	0.25	0.15	0.10

T a b l e 2. Mechanical properties of the used metal: AA 2024-0

Heat treatment	Yield strength (MPa)	Tensile strength (MPa)	Elongation (%)	Hardness (HB)
0	110	225	12	120

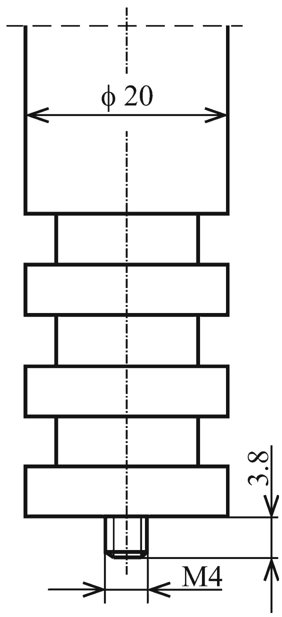

Fig. 1. The dimensions of the tool used for FSW (dimensions in mm).

2.2.2. *Friction stir welding (FSW)*

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

Pin profile was formed as M4 with 3.8 mm length, shown in Fig. 1.

FSW was performed by a 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 applications.

2.3. Sampling principles

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 [14]. Samples were extracted in accordance with EN 288-3 [15].

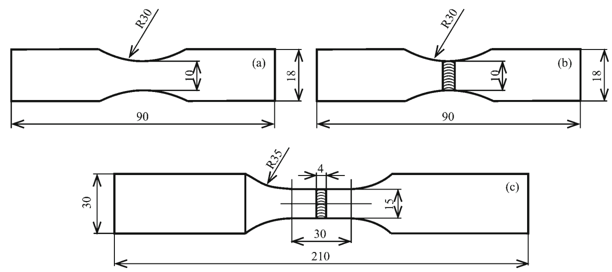

Fig. 2. a) Dimensions of fatigue base metal test specimens, b) dimensions of fatigue welding test specimens, c) tensile test samples.

According to 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 test samples were prepared according to characteristics of the testing machine for each welding method and base metal in standard sizes (DIN 50 142) (Fig. 2). Limit cycle number in all experiments was $N = 2 \times 10^6$ [16].

2.5. Hardness tests

On all samples of welded connections, Vickers hardness test was applied along a line using 500 g 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 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.

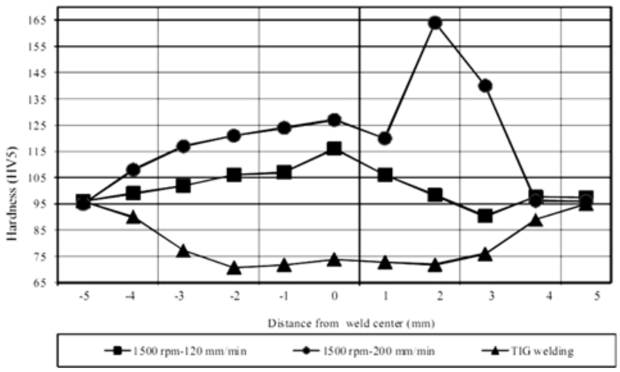

Fig. 3. Vickers hardness values of the samples.

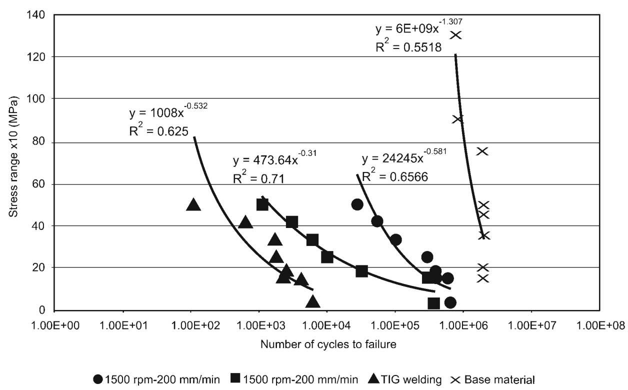

Fig. 4. Bending fatigue strength values of the test samples.

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.

3. Results and discussion

3.1. Hardness tests

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

3.2. Fatigue tests

Figure 4 shows bending fatigue strength test results of unwelded base metal, TIG welded and friction stir welded samples comparatively in one graphic.

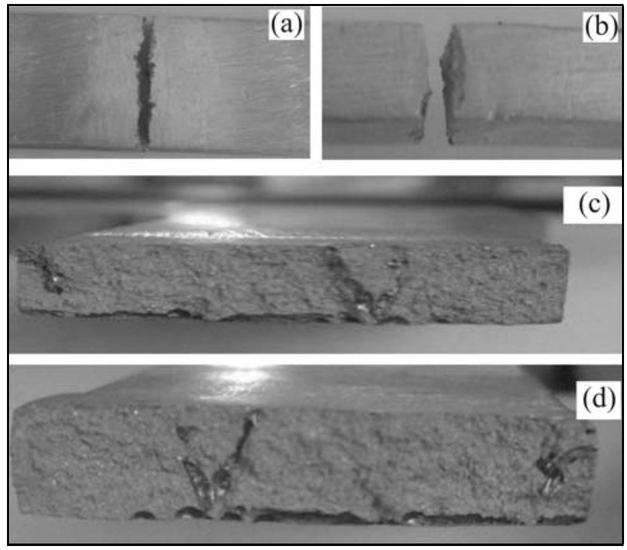

Fig. 5. Fractographs of TIG welded samples after tensile strength test.

3.3. Tensile strength tests

Figure 5 shows fracture zones of TIG welded samples after tensile strength test. Figure 6 shows fracture zones of FSW samples.

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

3.4. Visual examination results

Since TIG is a fusion welding method, distortion which occurs due to the 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 [17–19].

Single-sided FSW was performed. The bead of FSW was observed to be compatible with the literature [19]. 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 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 is 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 are consistent with the lit. [20–23].

3.5. Hardness

Hardness testing of all welds was performed by

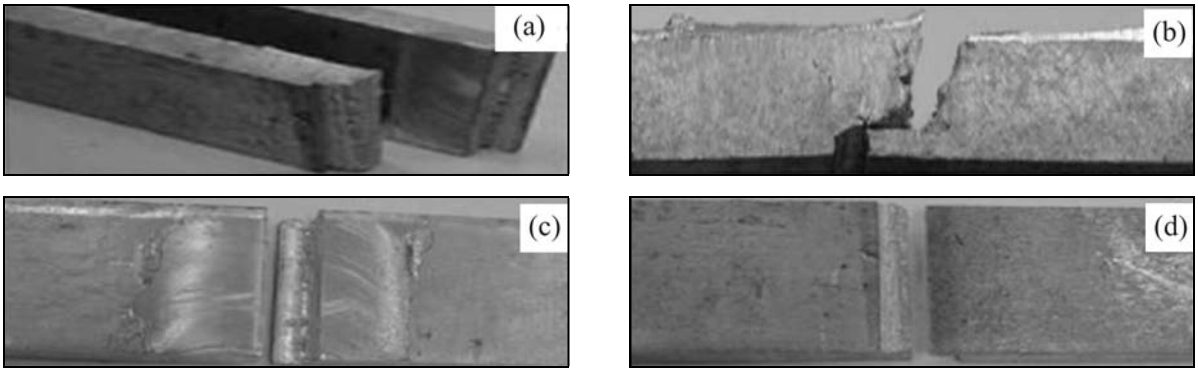

Fig. 6a–d. Fractographs of FSWed samples.

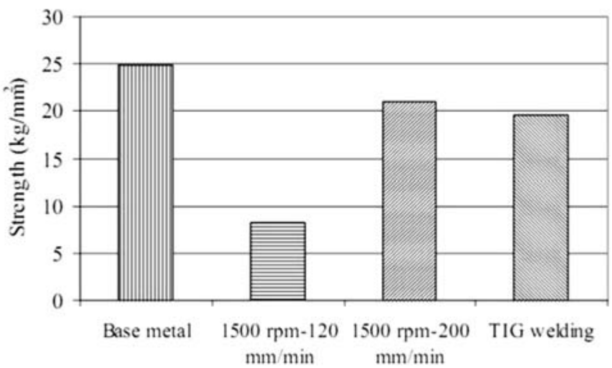

Fig. 7. Tensile strength values of the test samples.

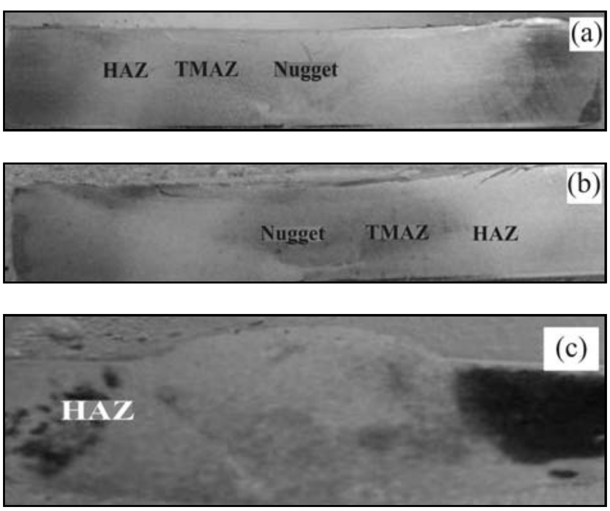

Fig. 8. Macrographs: a) FSW, 1500 rpm – 120 mm min^{-1}, b) FSW, 1500 rpm – 200 mm min^{-1}, c) TIG welding.

500 g load. Hardness was measured on a line perpendicular to weld bead. Results are shown in Fig. 3.

Hardness test results for TIG welds show that weld metal hardness is low compared to base metal. Fusion welding types are subject to high temperatures and have fairly wide HAZ in which hardening precipitates can experience over-ageing, causing phase transformation, which results in a general loss of mechanical properties. Base metal hardness is 95 HV. TIG weld metal hardness was measured as 70 HV. The highest hardness value for FSW joints was obtained from the samples that were joined with 1500 rpm – 200 mm min^{-1}, and is shown in Fig. 3. Low value on the other hand was measured on the samples that were joined by 1500 rpm – 120 mm min^{-1}. It is observed that when advancing from base metal (HAZ) to FSW welded, thermo-mechanically affected zone (TMAZ) hardness values are observed to increase. In Figs. 8 and 9 macrograph and microstructure of FSW and TIG welds are given, respectively. It is also observed that hardness value of weld bead (recrystallizing zone) continued to increase on plates welded with different parameters (Fig. 3). These results are supported by other researches conducted on AA 2024-O. High hardness value in welded region is a result of recrystallization and refined grain size [24, 25]. During FSW welding process the heat energy is formed due to the shoulder pressure and friction. This energy helps plastic deformation of aluminium sheets, and plastic deformation causes an increase in hardness values [26, 27].

When high speed and low rotation speed are used, it can be seen that there is less decrement in hardness value on welded zone. In high rotation, the amount of heat that enters the material is high, and this causes materials to cool more slowly, thus affecting hardness values. Compared to other parameters, in 1500 rpm – 120 mm min^{-1} test: because of high rotation and low pace, the lowest hardness value was measured [3].

The amount of heat input in FSW method affects microstructure and mechanical properties such as hardness and tensile strength. When welding speed is increased, it can be observed that the orientation of weld metal is also increased. Since with increased welding speed the heat input is reduced in FSW method, metal hardness is also a subject to change [28].

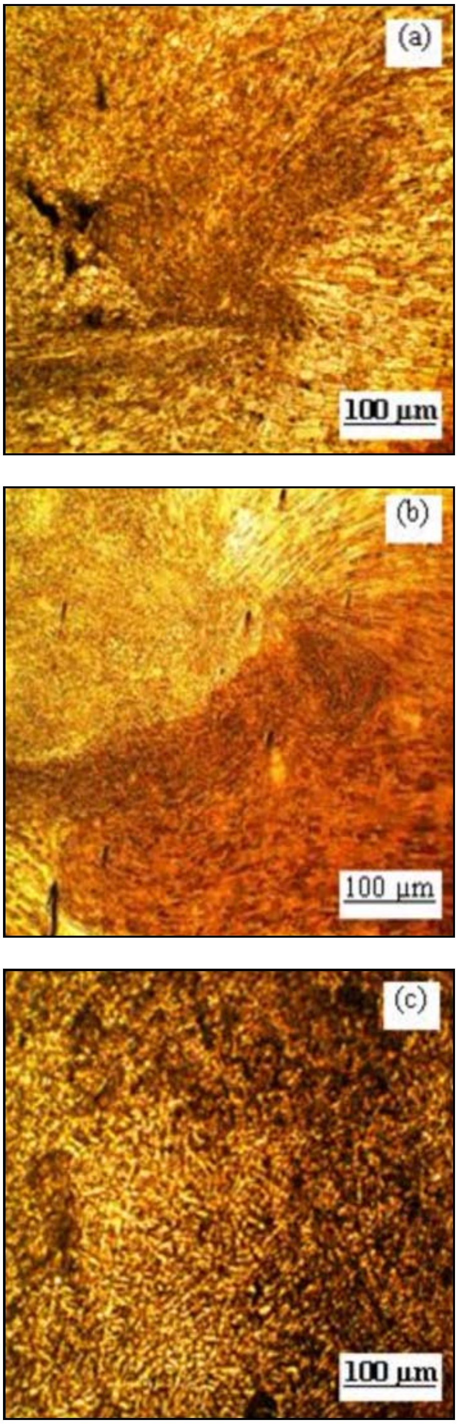

Fig. 9. Micrographs: a) FSW, 1500 rpm – 120 mm min^{-1}, b) FSW, 1500 rpm – 200 mm min^{-1}, c) TIG welding.

Because strengthening precipitations are dissolved in the weld zones of Al-alloys and cause material to soften, also a fine-grained microstructure is formed, and this causes hardness to decrease. The lowest hardness value was observed in extreme ageing zone, where precipitation particles in beads lose their strengthening abilities in these alloys [29].

The reason why hardness in weld centre is slightly higher than base metal hardness is explained with refined grain size and Hall-Patch relationship ($H_v = H_o + kH \cdot d - 1/2$) in lit. [25].

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 [16, 29].

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 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 [16, 29].

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

As hardness increases, fatigue strength increases as well; samples of 1500 rpm – 200 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 [30].

Also, when materials with high hardness value are used, they are expected to have high fatigue strength [16, 31].

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

As seen in the diagram in Fig. 4, bending-fatigue strength values of base metal are higher than joint samples with any welding method. Fatigue strength of TIG welded samples is observed to be lower than of base metal and also lower than the values of FSW samples with 2 parameters. Since hardness affects fatigue, these results are expected. TIG welded samples have the lowest hardness values. Highest fatigue strength is obtained from FSW samples with 1500 rpm – 200 mm min^{-1} parameter. So, these samples have also the highest bending fatigue strength values. This is also an expected result.

It is observed that with increased rotation speed and travel speed (1500 rpm – 200 mm min^{-1}), fatigue strength is also increased. When both rotation speed and travel speed are increased, heat input can be decreased, thus the width of HAZ can be controlled with parameters such as rotation speed and travel speed.

3.7. Tensile tests

It was observed that fracture occurred at the TMAZ. 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 1500 rpm – 200 mm min^{-1}.

It was observed that on FSWed samples, fractions occurred in TMAZ zone and compared to fusion welding methods, strength values were higher.

4. Conclusions

4 mm thick AA 2024-O 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 welded samples similar to tensile strength.

4. In FSW with constant rotation speed, hardness increases with increasing travel speed. With 1500 rpm – 200 mm min^{-1} rotation and travel speed, respectively, hardness, tensile strength and bending fatigue strength increased compared to 1500 rpm – 120 mm min^{-1} rotation and travel speed. This is because heat input was less and heat affected zone was narrower.

5. In 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 AA 2024-O, which is difficult to weld with fusion welding methods.

Acknowledgements

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