The impact of heat input on the microstructures, fatigue behaviors, and stress lives of TIG-welded 6061-T6 alloy joints

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Abstract
This work shows that heat input is an important parameter that influences microstructural changes in the heat-affected zones (HAZs) of TIG-welded 6061-T6 alloy joints and their fatigue behavior. Double-shielded TIG samples were welded using various heat input parameters and a gas mixture of 50% He and 50% Ar was used to produce an improved weld penetration, their mechanical properties and microstructures of the samples were compared to those of the unwelded alloy. The mechanical properties of the aluminum alloys and the welding zones were evaluated by performing tensile and fatigue tests. The fatigue behaviors of the 6061-T6 joints welded with different heat inputs were assessed by performing cyclic fatigue experiments. Their microstructures were examined via optical microscopy and scanning electron microscopy (SEM). Grain coarsening was observed in the fusion zones (FZs), and heat input during TIG welding made the HAZs larger. Applying the lowest heat input value yielded samples with poor ultimate tensile strength, which was attributed to partial penetration and the presence of pores in the welded joints. The oxygen content of the weld pool depended directly on the shielding method and the surface temperature distribution.

1. Introduction
The popularity of Al–Mg–Si alloys can be attributed to their excellent chemical and mechanical properties. These include corrosion resistance, good formability, and weldability, so they are increasingly being adopted in multiple industries. However, welding dramatically reduces the fatigue strength of these alloys relative to that of the unwelded base metals. In this study, it is explored how different welding heat input parameters influenced the fatigue performance of an Al–Mg–Si alloy. As a result, this information could be used to fabricate new and improved fatigue-resistant structures, which could prevent problems associated with structural fatigue under service conditions. Over 90% of components that fail during service break due to structural fatigue [1], and fatigue is the primary reason that welded joints in mechanical structures fail. Fatigue is influenced by the microstructure of a material, which has been shown to strongly depend on processing parameters, particularly heat input during welding [2]. Welding is the most common joining method, and fatigue resistance is a critical factor in mechanical design. However, welded joints can be susceptible to fatigue [3], and 70% of the cracking failures in welded joints are due to fatigue [4].

Several authors [5–9] have studied the impacts of different processing parameters on the fatigue strength of 6XXX alloys. Fatigue resistance is influenced by many factors, such as the presence of cracks, porosities, bubbles, residual stress, temperature, and corrosive media. In a joining process like welding, heat input strongly impacts the performance of the welded joint and decreases its fatigue strength.

Most problems associated with welded 6061-T6 aluminum alloys are due to over-aging of the weldments, which negatively impacts the mechanical performance of the joints [10–14]. It has recently been found that variations in the mechanical properties of welded aluminum joints are related to defects that are introduced in...
Variability may also be due to a lack of fusion or incomplete penetration \[15, 16\]. The large amount of heat generated during the welding process can lead to inhomogeneous heating and cooling in the region surrounding a welded joint, which is called the heat-affected zone (HAZ). The HAZ impacts the fatigue behavior of a welded structure, which is the most likely cause of failure. The way in which heat input is regulated directly affects the welding zone after passing the TIG torch, so it has an impact on fatigue behavior. A large amount of heat input during the TIG process enables rapid deposition, fast welding, and deep penetration. However, excessive heat input causes several problems, such as over-aging, shrinkage, undercutting, and distortion; being this particularly problematic for thin aluminum sheets.

Temperature is a major factor in terms of thermal effects, which lead to microstructural changes that impact the behavior of a material \[12\]. The heat supplied by the electric arc in a welding process causes significant microstructural changes in a welded material that affect its mechanical properties \[17–19\]. Various authors have studied the influence of temperature on the mechanical properties and microstructures of heat-treated aluminum alloys \[18–20\]. However, the relationship between heat input during the TIG welding process and the fatigue behavior of Al–Mg–Si alloys has not been thoroughly investigated. Different welding heat inputs were investigated in this study to mitigate distortion and residual stress in metallurgical joints. The fundamental motivation of this work is to improve fatigue resistance and develop a welding process that is more environmentally friendly and economical than other welding processes and post-heating treatments. Thus addressing current ongoing challenges due to safety concerns, legal constraints, and maintenance procedures.

### 2. Experimental

#### 2.1. Materials

6061-T6 300 × 60 × 6 mm³ commercial grade aluminum alloy plates were used for the welding tests. The chemical composition of the as-received commercial 6061-T6 alloy is listed in Table 1. The samples where ground and cleaned with acetone to remove surface oxides. The samples were welded in a single pass using ER4043 filler metal (Ø 1.6 mm) to fabricate double-V joints.

Welding was performed longitudinally relative to the rolling direction and localized at the centers of the top joints of the machined tensile and fatigue testing specimens. The experiments were aimed at preventing welding defects, such as pores, distortions, and heat-induced cracks. The variable TIG welding parameters are listed in Table 2, and the welding preparation parameters are shown in Table 3. The shielding gas had a constant composition of 50% helium and 50% argon since it has been shown to provide improved heat distribution, penetration and overall a faster welding process \[21\].

| Alloy | Al | Si | Fe | Cu | Mn | Mg | Cr | Ti | Pb |
|------|----|----|----|----|----|----|----|----|----|
| Al 6061-T6 | 97.17 | 0.65 | 0.64 | 0.19 | 0.07 | 1.00 | 0.21 | 0.02 | 0.05 |

*Table 1. Chemical composition of Al 6061 T6 (wt%).*

| Samples | Amperage (A) | Voltage (V) | Current | Shielding gas | Flow rate (l min⁻¹) | Heat input (J mm⁻¹) |
|---------|--------------|-------------|---------|---------------|---------------------|-------------------|
| A       | 220          | 18          | AC      | Ar–He         | 25                  | 356               |
| B       | 230          | 18          | AC      | Ar–He         | 25                  | 373               |
| C       | 240          | 18          | AC      | Ar–He         | 25                  | 389               |

*Table 2. TIG welding parameters.*

| Welding conditions | Description |
|--------------------|-------------|
| Joint type         | Double-V    |
| Electrode          | 3/16” pure W-green |
| Filler             | ER4043      |
| Plate separation distance | ½ e |
| Pointed            | 10 mm for each 50 mm |
| Cleaning procedure | Steel brush and acetone |
| Preheating         | No          |
| Technique          | Push        |
| Welding rate       | Manual (10 mm s⁻¹) |

*Table 3. Welding preparation conditions.*
Other parameters that remained constant were the welding voltage (18 V) and welding speed (10 mm s\(^{-1}\)). Equation (1) was used to determine the welding heat input (L).

\[
L = \eta (UI/V)
\]  

The welding voltage (U), current (I), and speed (V) were used to calculate L assuming a TIG welding efficiency (\(\eta\)) of 0.9. [22]

Unwelded samples and samples welded with heat inputs of 356 J mm\(^{-1}\), 373 J mm\(^{-1}\), and 389 J mm\(^{-1}\) were prepared to study the effects of heat input on microstructure and fatigue performance. The welded and unwelded aluminum alloy specimens were mounted and polished using standard metallographic methods. Their microstructures were examined using a GX71 optical microscope (Olympus, Japan) and a LEO 1450 VP scanning electron microscope (Carl Zeiss, Germany). A model 4206 tensile testing machine (Instron, USA) was used to perform tensile tests at a rate of 1 mm/min. Samples for the tensile tests were prepared according to the ASTM E-8 guidelines [23]. Each reported tensile result was the average value obtained after testing three samples from the same joint.

The fatigue tests were performed using a RBT 200 rotating fatigue machine (Fatigue Dynamics, USA). Circular test tubes with a constant radius were used in accordance with the ASTM E-466 standard method [24]. The specimens used for the S–N tests were welded perpendicular to the applied load and to the material rolling direction. A schematic illustration of the specimens is shown in figure 1.

A total of eight specimens from each group were polished to remove superficial defects. A rotating cantilever was used to measure the fatigue strengths of the samples at five maximum stress levels according to the staircase method [25] for fatigue lifetimes up to \(1 \times 10^7\) cycles. An increase or decrease in the stress applied in a given step depended on whether the sample remained intact or failed in the previous experiment. The maximum stress levels were based on the yield stresses of the joints and ranged from 30% to 70% of the yield stress. A stress ratio (R) of 0.1 and a frequency interval of 50–80 HZ were employed. The threshold for infinite life was \(1 \times 10^7\) cycles based on previous reports [26, 27].

3. Results and discussion

3.1. Aluminum alloy microstructure

An optical micrograph of the base metal is shown in figure 2. The microstructure of the base material was characterized by homogeneous and regular equiaxed grains with a grain size of 4 (according to ASTM). A SEM image of a welded Al6061-T6 sample is shown in figure 3. Fine Mg\(_2\)Si precipitates formed along the grain boundaries during the artificial aging process and appeared dark gray in the SEM image, while the lighter regions contained Fe\(_3\)SiAl\(_{12}\). The high iron content of the sample could be attributed to the composition of the filler metal [28].

Microstructural changes associated with increasing heat inputs can be seen in figure 4. The welded joints had wide HAZs, fusion zones (FZs), and base metal areas. The FZs contained equiaxed dendritic networks with fine microstructures, which resulted from rapid cooling [28]. The HAZs contained elongated grains oriented in the direction of heat flow, but the microstructures were not thermally affected near the base material. The grains clearly became more refined between the base metal and the FZs due to thermal gradients. The grain sizes ranged from 4 (according to ASTM) in the base metal to 6 (according to ASTM) in the FZs. All of this essentially depended on the composition of the alloy, the cooling rate, and the heat transmitted by the electric arc to fuse the metal [2].
Quantitative metallographic methods [29] were used to calculate the widths of the HAZs and the average grain sizes in the FZs (figure 5) (table 4). Increasing the heat input from 356 J mm\(^{-1}\) to 389 J mm\(^{-1}\) widened the HAZs from approximately 295 μm to 410 μm. The peak temperatures of the molten pools were lower with heat inputs of 356 J mm\(^{-1}\) and 373 J mm\(^{-1}\), so the HAZs in figures 4(a) and (b) were narrower. Solidification took longer when the heat input was 389 J mm\(^{-1}\), so more heat was transferred to the base metal. The HAZs were consequently wider, as shown in figures 4(c), (d). Increasing the heat input thus increased the width of the HAZ and the size of grains within the HAZ, which was consistent with the results of a previous study [2]. This phenomenon has been attributed to the recrystallization of AZ series magnesium alloys, in which grain coarsening occurs easily [30], and although recrystallization occurred for all the conditions, a higher heat input provides a higher driving force for migration of grain boundary to occur, result in a higher rate of grain growth [31].

### 3.2. Tensile properties

The welded samples and the as-received material were subjected to tensile tests, and the yield strengths and ultimate tensile strengths of the Al 6061T-6 aluminum alloy joints were evaluated. The average values calculated after each test are shown in table 5. The influence of heat input on the ultimate tensile strength of the welded joints is illustrated in figure 6. At the lowest heat input value of 356 J mm\(^{-1}\), pores formed in the welded seam, and partial penetration was observed in the welding. Pore formation may have been due to the introduction of air from interfacial regions on the plate into the melt pool, which resulted in the formation of pores in the welded seam. This affected the ultimate tensile strength of the welded seam (40 MPa), which was only 18% of that of the base metal (220 MPa). These results showed that insufficient heat input during the TIG welding process...
Figure 4. Metallographic images of specimens welded with heat inputs of (a) 356 J mm\(^{-1}\), (b) 373 J mm\(^{-1}\), and (c) 389 J mm\(^{-1}\). (d) SEM image of a 6061-T6 joint after TIG welding at 389 J mm\(^{-1}\).

Figure 5. Average grain size in the FZ and width of the HAZ obtained after welding at each heat input value.

Table 4. Obtained average grain size in the FZ and width of the HAZ with their corresponding standard deviation.

| Heat input (J mm\(^{-1}\)) | Average grain size (µm) | Width of HAZ (µm) | (\(\overline{E}\)\(\overline{\sigma}\)) | (\(\overline{E}\)\(\overline{\sigma}\)) |
|-----------------------------|-------------------------|------------------|-----------------|-----------------|
| 356 J mm\(^{-1}\)          | 34                      | 295              | 1.36            | 11.8            |
| 373 J mm\(^{-1}\)          | 36                      | 340              | 1.44            | 13.6            |
| 389 J mm\(^{-1}\)          | 45                      | 410              | 1.8             | 16.4            |
facilitated defect formation in the aluminum alloy, which significantly decreased the tensile strength of the welded joints, particularly a hotter weld pool increases the solidification time, therefore allowing gas bubbles to escape and reducing the risk of gas entrapment \[32\]. The ultimate tensile strength of the welded joints increased when the heat input was increased. The tensile strengths of the welded joints reached a maximum of 74 MPa, which was 34% of the tensile strength of the base metal. This was achieved with a heat input of 389 J mm\(^{-1}\), which resulted in less partial penetration and pore formation in the welded seams (figures 6(a) and (b)).

Although according to the Hall-Petch equation a material with a smaller grain size is expected to have higher tensile strength and hardness, in this case, the produced welding defects associated with the low heat input conditions (such as partial penetration and gas entrapment), drastically affects the resulting mechanical properties \[31\]. These results were consistent with those reported by Peng et al \[2\], who performed TIG welding with aluminum samples under various heat input conditions. As a result of this, it is exhibited that at low heat input conditions, the resulting mechanical properties are negative impacted due to a higher presence of welding defects, hence, higher heat input is preferred in order to reduce the risk of welding defects and therefore obtaining a higher UTS of the welded joint \[31\].

### 3.3. Fatigue behavior

The staircase method is commonly used to determine the average fatigue limit of a component or material over a specified number of cycles. The equation proposed by Rice \[25\] to determine the fatigue limit is shown in equation (2).

\[
\mu = \delta_0 + \Delta S \left( \frac{\sum i \tau_i}{n_r} + \frac{1}{2} \right) \quad n_f > n_r
\]
Where $\delta_0 =$ lowest or initial stress level, containing at least one failed (level $i = 0$), $\Delta S =$ stress increment between steps, $n_r =$ number of run-outs, $n_f =$ number of failure events $r_i =$ number of events at the $i$ level, $i =$ stress level index

The fatigue testing procedure and other details are described elsewhere [33]. Sequential fatigue tests were performed by applying different loads (figure 7), and stress increases were determined using the staircase method. Once the results were obtained, the Rice equation was used to calculate the fatigue limits for $1 \times 10^7$ cycles (table 6). Nineteen of the thirty-two specimens failed, and failure most often occurred in the welding zones. This was due to thermal effects that generated defects in the weld seams.

Typical cavity shrinkage and gas pores are visible on the fractured surfaces of sample cross sections shown in figures 8(a) and (b), respectively. Pores reduced the duration of crack initiation, so crack growth during much of the fatigue life led to rapid fracture. The microstructures obtained after solidification in a conventional fusion welding process are strongly influenced by such defects. Pores are more likely to form in the weld zone, which is a common phenomenon in fusion welds [34]. A high concentration of stress due to pore shrinkage leads to fatigue because cracks are initiated around pores on or near the specimen surface. Consequently, the fatigue life is significantly reduced. Pore defect formation is due to incomplete hydrogen diffusion in the melt during solidification. Another type of defect is caused by cavity shrinkage during solidification, which is due to a lack of material flow in the spaces between connected dendrites [35]. The fractographic study revealed the importance of welding defects in failure initiation, which significantly reduced fatigue life.

The fatigue behavior of the unwelded and welded joints is illustrated in the S–N curves shown in figure 9. In most cases, the S–N curves became progressively flatter as the fatigue strength decreased. It was quite clear that each TIG welding process greatly reduced the fatigue resistance of the 6061-T6 alloy joints. The joints welded at 240 A (389 J mm$^{-1}$) exhibited better fatigue performance than the joints welded at 220 A (356 J mm$^{-1}$) and 230A (373 J mm$^{-1}$). The joints welded with a heat input of 389 J mm$^{-1}$ had the highest fatigue strength, which was 40% of that of the base metal. This was attributed to the presence of fewer welding defects, including partial penetration, pores, and shrinkage cavities, in the welded seams. These welded joints had better mechanical

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**Table 6. Summary of fatigue strength and area reduction percent.**

| Joint type | Fatigue strength (MPa) | Reduction percent (%) |
|------------|------------------------|-----------------------|
| As unwelded | 71                     | 100                   |
| 220 A (356 J mm$^{-1}$) | 10.5                  | 85                    |
| 230 A (373 J mm$^{-1}$) | 11.3                  | 84                    |
| 240 A (389 J mm$^{-1}$) | 28.7                  | 60                    |

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Figure 7. Sequence of tests performed to determine fatigue limits according to the staircase procedure.
properties than those welded with less heat input, and the welded regions in the joints had ideal microstructures. These features explained their superior performance.

These results showed that the fatigue behavior of the welded joints and heat input during welding were inherently related. Heat input influenced the formation of pores, micro-crack formation, and the concentration of stress, which strongly impacted the fatigue life of the welded joints. In this research, welding with the maximum heat input afforded the longest fatigue life. However, higher heat inputs are thought to promote the formation of defects that reduce the fatigue life of joints [36].

Figure 8. Welding defects formed under different welding conditions. (a) Shrinkage cavities (220 A, 356 J mm\(^{-1}\)), (b) pores (230 A, 373 J mm\(^{-1}\)), and (c) partial penetration (240 A, 389 J mm\(^{-1}\)).

Figure 9. S-N curves of the unwelded and welded Al 6061 T6 joints.
4. Conclusions
This paper reports the investigation of the influence of heat input on the fatigue strength at high cycle fatigue (10^7 < Nf) testing, as well as fatigue life estimation of specimens and components by multiple approaches for TIG-welded 6061-T6 alloy joints.

- The fatigue strength and fatigue life of TIG-welded 6061-T6 alloy joints were greatly increased by an increase in heat input. Among the three welded joints, the joints welded at 240A (389 J mm^-2) exhibited higher fatigue strength and fatigue life compared to the others.
- The fatigue performance of TIG-welded 6061-T6 alloy joints is greatly influenced by welding defects (such as pores and shrinkage cavities) which have a significant effect on fatigue life.
- Higher heat input conditions result in an increase in HAZ width and grain size of the FZ of the Al6061-T6 TIG welded joints.
- Low heat input values lead to inhomogeneous heating and lack of fusion, generating defects during the welding process, which results in low tensile strength values of the 6061-T6 TIG welded joints.

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