A Study on Welding Characteristics, Mechanical Properties, and Penetration Depth of T-Joint Thin-Walled Parts for Different TIG Welding Currents: FE Simulation and Experimental Analysis

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Abstract: Considering the effect of heat input of tungsten inert gas (TIG) arc welding for T-joint welding of thin-walled parts of aluminum alloy 6061-T6, here, the welding characteristics are analyzed via the finite element method. The experiments are carried out using scanning electron microscope (SEM), optical microscope (OM), and tensile test of specimens to investigate the microstructure variation of the weld zone (WZ), heat-affected zone (HAZ), and base metal (BM), and the mechanical properties of the T-welded joint. The mechanical properties of the T-welded joint are explored and assessed combined with the tensile test in terms of yield strength, tensile strength, and Vickers hardness. Furthermore, the effects of different welding currents on welding penetration variation under welding deformation are thoroughly investigated, and the appearance of porosity and incomplete fusion defects of T-welded joints are clearly illustrated. The results show that the yield and tensile strength of T-welded joints, respectively, account for less than 37% and 74% of the base metal (BM) strength. Moreover, the welding penetration depth and microstructure of T-welded joints are deeply affected by the welding current. The maximum penetration depth is achieved at about 2.18 mm under the maximum welding current, and partial welding defects emerged, affecting and reducing the mechanical properties of the welded joint. It is expected that these results will provide an analysis foundation for optimization of the welding process, suppression of welding defects, and promotion of mechanical properties for thin-walled parts in the future.

Keywords: T-welded joint; welding characteristics; welding defects; mechanical properties; finite element simulation

1. Introduction

Welding assembly techniques have been widely applied to various engineering fields, such as automobile, radar antennas, aircraft, marine equipment, etc. [1]. Their service behaviors and the mechanical properties of welded joints are of crucial importance for the overall welding assembly structure [2,3]. However, those properties are affected by various factors, such as welding process parameters, temperature field during the melting and cooling processes, welding defects, microstructural formation, etc. [4]. At present, a larger number of researchers focus on the characterization of the microstructure and the analysis of mechanical properties of similar or dissimilar metal sheets with lap joint, butt joint through friction stir welding [5–8], A-TIG welding [9], laser welding [10], laser-TIG hybrid welding [11], and electron beam welding [12]. For example, considering the effect of welding processes involving the tool rotational speed, welding speed, rotation rate, etc.,
some researchers adopted friction stir welding to investigate temperature distribution, microstructure evolution, tensile properties, formation mechanisms, and the evolution of micro-void defects of joints, which promotes the mechanical properties and their welding quality for the same or dissimilar metal joints [8,13,14]. In addition, some scholars have also conducted in-depth research on them with other welding techniques. For instance, Mehdi et al. [15] investigated the effect of friction stir processing on TIG welding to improve the mechanical properties and wear resistance behavior of the TIG-welded joint of AA7075 and AA6061, considering tool rotational speeds and filler materials. Ramkumar et al. [16] studied the microstructure traits and structural integrity of Ti-6Al-4 V welds of 5 mm thickness with A-TIG welding considering the activated flux. Kulkarni et al. [17] studied the dissimilar metal weldments between P91 steel and AISI 316L austenitic stainless-steel by A-TIG and analyzed the effect of Incoloy interlayers on the microstructure and tensile strength of weld joints. Fadaefard et al. [18] explored the microstructure, mechanical, and nanomechanical properties of the TIG welding butt joint for AA6061-T6 with ER5356 filler in as-welded and after post-weld heat treatment. Furthermore, Ardghail et al. [19] proposed a finite element model of dislocation mechanics to predict the thermo-mechanical fatigue performance of welds for multi-pass gas tungsten arc welding, considering the effect of temperature, microstructural, and mechanical property. Junaid et al. [20] comparatively analyzed the variation results of microstructure, mechanical properties, and residual stress for Ti-5Al-2.5Sn titanium alloy through TIG, EBW, and LBW, which is intended to promote those welding properties. Hakem et al. [21] researched the microhardness, tensile strength, impact toughness, and electrochemical behavior for AA6061-T6 aluminum alloy of TIG welded considering microstructure and precipitation phenomena. Baskoro et al. [22] proposed an automated or intermittent wire feeding method with one combination proportion of filler metal under different TIG welding parameters to analyze the macrostructure, microstructure, and mechanical properties for AA6063-T5. Xuan et al. [23] analyzed the effect of joint gap, welding parameters, and arc length on the weld appearance, microstructure, and mechanical properties for Invar36 alloy plates with single-pass keyhole TIG welding. There have been many studies, such as in the abovementioned literature, focusing on the microstructure evolution and mechanical properties of welded joints through different welding techniques.

However, in the actual welding process, the welding structure is susceptibly subject to welding deformation [24]. The generated welding residual stresses and distortions that can change the performance and reliability of the welding structure are closely related to welding heat input, joint constraint conditions, etc. Especially, welding distortion can have a great influence on the dimensional accuracy of welding assembly, structure strength, and fabrication cost [25,26]. There has been a lively interest in the prediction and assessment of welding residual stress and distortion. For example, Wei et al. [27] predicted the welding-induced deformation for large, welded structures during the assembly process with inherent strain theory and the interface element method, considering the local shrinkage caused by heat input, welding sequence, and external restraint. Khoshroyan et al. [28] adopted the 3D thermo-mechanical coupled FE method for welding deformation, residual stress, and temperature distribution, and the vertical deformation, angular distortion, transverse shrinkage, and residual stress in the plate and stiffener are greatly affected by welding speed, sequence, and welding current. Cai et al. [29] proposed a fuzzy finite element model to assess the welding distortion in T-joint fillet welding with the eigenstrain method, combining with thermal elastoplastic finite element results, which explains the generation mechanism of welding distortion related to the formation of the heat-affected zone. However, the abovementioned reports have been less focused on the correlation studies of the mechanical properties, and the welding penetration of the welded joint, which is affected by the welding deformation. Therefore, in this work, the thin-walled parts of 2 mm in thickness are welded to be T-joint structures by the TIG welding process, and the effect of different welding currents on the welding characteristics, involving welding deformation, residual stress, and temperature distribution, is analyzed through FE simula-
tion. Meanwhile, the mechanical properties and microstructure variation of T-welded joints under welding deformation, and the effect of the emerged welding defects on mechanical properties, are performed by conducting many kinds of measurement experiments.

2. Materials and Their Property Parameters

The welding characteristics of thin-walled part structures play an imperative role in the electromagnetic performance of the radar antenna, that is assembly welded by a large number of thin-walled parts. Therefore, in this work, the T-joint thin-walled part from an antenna internal structure is as a research object to investigate its welding characteristics and the mechanical properties of the welded-joint. In addition, according to the material compositions in [30–32], the used thin-walled parts of Al6061-T6 material are welded by adopting welding wire ER4043 in the welding process. Their chemical compositions are presented in Table 1. The T-joint thin-walled part of 2 mm is taken as an example, and its marked size is shown in Figure 1.

Table 1. Chemical composition of materials.

| Element (%) | Si  | Mg  | Fe  | Cu  | Mn  | Zn  | Ti  | Cr  | Al  |
|-------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| Al6061-T6   | 0.40–0.80 | 0.80–1.20 | ≤0.70 | 0.15–0.40 | ≤0.15 | ≤0.25 | ≤0.15 | 0.04–0.35 | Bal. |
| ER4043      | 4.5–6.0 | ≤0.05 | ≤0.80 | ≤0.03 | ≤0.05 | ≤0.10 | ≤0.20 | —   | Bal. |

Figure 1. T-joint thin-walled part structure.

Simultaneously, according to the relative parameters in [33], the variation curve for the thermal and mechanical characteristics of Al6061-T6 depending on the temperature is shown in Figure 2. To obtain the temperature variation of the welding and cooling process using ABAQUS, the Stefan−Boltzmann constant and the convective heat transfer coefficient were set as $5.68 \times 10^{-8}$ and $80\ J/(m^2\cdot s\cdot ^\circ C)$, respectively. Simultaneously, the latent heat was $3.9 \times 10^5\ J/kg$, and the solidus temperature and liquidus temperature were, respectively, $585\ ^\circ C$ and $659\ ^\circ C$. In addition, Poisson’s ratio is always 0.33 with temperature.
3. Welding Characteristics Analysis with FE Simulation

During welding assembly, the deformation of thin-walled parts is occurring. To investigate the mechanical properties of the T-welded joint under welding deformation, before the actual welding assembly for T-joint thin-walled parts of 2 mm, the red zone of the two sides of the web plate and the base plate are connected and fixed through spot welding, as shown in Figure 1. Therefore, when the welding characteristics of T-joint thin-walled parts are analyzed through FE simulation, the fixed constraint zones are the red zone of the two sides of the thin-walled parts through fixing nodes of the red zone of two sides for the FE model.

In addition, to better understand the effect of welding heat input on the welding characteristics, the correlation between welding characteristics, mechanical properties, and welding penetration depth of the T-welded joint is obtained. When the simulation was carried out, the welding voltage of 20 V, welding speed of 3 mm/s, and welding efficient of 0.75 remained the same, and the corresponding welding currents were, respectively, 100, 170, and 220 A. Simultaneously, the front length, rear length, width, and depth of the adopted heat source model of the double ellipsoid were, respectively, 1.5, 6, 2.5, and 2.5 mm, as shown in Figure 3.

In this work, the adopted double ellipsoidal heat source model was that established by Goldak et al., with the front and rear quadrant’s power density [34]. The energy fractions of the front and rear half ellipsoid are, respectively, \( f_f \) and \( f_r \), where \( f_f + f_r = 2 \). Then, the power density distribution function of the front and rear half ellipsoid is as follows [1,34]:

\[
q(f) = \frac{6\sqrt{3}f_fQ_f}{\pi^{3/2}a_fbc} \exp \left( -3 \left( \frac{x}{a_f} \right)^2 + \left( \frac{y}{b} \right)^2 + \left( \frac{z}{c} \right)^2 \right) 
\]

\[
q(r) = \frac{6\sqrt{3}f_rQ_r}{\pi^{3/2}a_rbc} \exp \left( -3 \left( \frac{x}{a_r} \right)^2 + \left( \frac{y}{b} \right)^2 + \left( \frac{z}{c} \right)^2 \right) 
\]

where \( Q_f \) and \( Q_r \) represent the heat input for front and rear parts of the ellipsoid, \( a_f \) and \( a_r \) denote the length of front and rear parts of the ellipsoid, and \( b \) and \( c \) are the width and depth, respectively.
According to the above formulas, the heat source model was established by coding DFLUX subroutine using FORTRAN combined with ABAQUS in this work. Furthermore, the total welding time was 70 s, and the cooling time was 200 s. Hereby, the FE model of T-joint thin-walled parts as shown in Figure 4 was built to analyze the variation of welding characteristics.

**Figure 3.** The heat source model of the double ellipsoid Reprinted with permission from Ref. [35] 2022 Springer Nature.

Simultaneously, the total heat input, $Q$, is closely related to welding voltage, $U$, welding current, $I$, and welding efficiency, $\eta$, and its expression is as follows [35,36]:

$$Q = \eta \cdot U \cdot I$$

(3)

According to the above formulas, the heat source model was established by coding DFLUX subroutine using FORTRAN combined with ABAQUS in this work.

Furthermore, the total welding time was 70 s, and the cooling time was 200 s. Hereby, the FE model of T-joint thin-walled parts as shown in Figure 4 was built to analyze the variation of welding characteristics.

**Figure 4.** FE model of T-joint thin-walled parts.

*Simulation Results Analysis*

According to the abovementioned conditions, the welding deformation and residual stress distribution of T-joint thin-walled parts after ending the cooling time were obtained through FE simulation, as shown in Figure 5. In Figure 5, it can be obviously seen that the T-joint thin-walled parts were subjected to different extents of deformations and warpage of the base plate during the welding process. From the perspective of maximum value, the maximum deformation value was about 5.94, 10.20, and 11.36 mm when the welding currents were 100, 170, and 220 A, respectively. At this point, the warpage degree of the base plate was the largest for the welding current of 220 A. These results show that when other welding process parameters remained unchanged, the welding deformation increased with the increment of the welding current. Namely, according to the Equation (3), when the welding current increases, the heat input is also increasing, and the welding deformation increases to a certain degree.
were, respectively, 100, 170, and 220 A. The residual stress variation of node p8 in Figure 6f within 0–100 s in Figure 6e. Then, after the welding step finished, the welding cooling was within a small range over a period of time, which can be seen from the enlarged view T-welded joint under welding deformation. In Figure 6e,f, it can be seen that the welding variation of welding properties, and their variation curves are shown in Figure 6. A better fused. After the metal solidified until it was completed. At this time, the residual stress released at 220 A was the highest. Therefore, this variation result of residual stress was produced.

Additionally, to better understand the variation of welding deformation, residual stress, and temperature for different welding currents, a series of nodes (p1–p10) near the second weld obtained according to the welding sequence in Figure 4 were chosen to analyze the welding characteristics of T-joint thin-walled parts. For those key nodes near the weld, the distance from the weld edge line was 2 mm on the enlarged view of the T-welded joint in Figure 4. In this work, the nodes p3 and p8 were taken as examples to analyze the variation of welding properties, and their variation curves are shown in Figure 6.

As shown in Figure 6a,b, it can be obviously seen that the welding temperature was constantly changing during the welding process until reaching the ambient temperature of 20 °C. Overall, the welding temperature increased with the increment of the welding current. The reason for this result is that the welding heat input increases when the welding current is increasing, and the welding temperature will rise during the welding process. In Figure 6c,d, the welding deformation also increased with the increment of the welding current. Meanwhile, when the welding finished after 70 s, the welding cooling lasted until 270 s; at this time, the T-joint thin-walled parts are no longer warped and deformed, which has a definite deformation value. Hereby, it will provide an analysis basis for investigating the correlation between the mechanical properties and the welding penetration depth of the T-welded joint under welding deformation. In Figure 6e,f, it can be seen that the welding residual stress also changed all the time within 70 s. Due to the effect of the first weld on the welding properties of the nodes near the second weld, the residual stress fluctuated within a small range over a period of time, which can be seen from the enlarged view within 0–100 s in Figure 6e. Then, after the welding step finished, the welding cooling was carried out, and the weld metal was gradually solidified until it was completed. At this time, the residual stress was released and sharply increased at about 72, 80, and 100 s, as shown in Figure 6e, until reaching the balance of residual stress, when the welding currents were, respectively, 100, 170, and 220 A. The residual stress variation of node p8 in Figure 6f...
is similar to node p3. On balance, after reaching the equilibrium, the residual stress under the welding current of 220 A was the smallest, compared to the welding currents of 100 and 170 A. Since the welding heat input increased, the weld metal and base metal were better fused. After the metal solidified, the residual stress was released to a certain degree. At this time, the residual stress released at 220 A was the highest. Therefore, this variation result of residual stress was produced.

Figure 6. Variation curves of welding properties with time for different welding currents. (a) Temperature variation curve of p3, (b) temperature variation curve of p8, (c) welding deformation curve of p3, (d) welding deformation curve of p8, (e) residual stress variation curve of p3, and (f) residual stress variation curve of p8.
After understanding the welding characteristics' variation rules of T-joint thin-walled parts, the following sections discuss the variation of mechanical properties and the welding penetration depth of T-welded joints that have welding deformation. Especially, in this work, the welding-deformed T-joint thin-walled part structure was used for preparation of the tensile specimens, to obtain the mechanical properties of the T-welded joint.

4. Experimental Procedure

To make the FE simulation correspond to the actual welding conditions of T-joint thin-walled parts, the welding conditions, including welding voltage, welding speed, etc., that are used for the manual TIG procedure remained unchanged, the actual welding currents were set as 100, 170, and 220 A, and the Argon gas flow was 10–12 L/min. Regarding the filler material used in the welding process, the ER4043 wire diameter was 2.0 mm. Hereby, the web plate and base plate of T-joint thin-walled parts were welded together to obtain the tensile specimens to investigate the mechanical properties and microstructure morphology of the T-welded joint.

Regarding the preparation of the tensile specimens, two tensile test specimens obtained from the T-joint thin-walled parts under conditions of different welding currents were cut by a wire-cutting machine tool, as shown in Figure 7. A total of 9 samples were subjected to tensile testing to obtain more accurate results in accordance with relevant standards, and the cross-section area of the specimens was 18 mm × 2 mm. Additionally, the specimens were clamped with fixtures on the SANS electronic universal testing machine, and the tensile rate was 1 mm/min, as shown in Figure 8. As a result, the force-displacement data for the acquired specimens under different welding current were obtained. Then, the true stress–true strain values were calculated by the following formulas [37]:

\[
\begin{align*}
\sigma_{\text{true}} &= \sigma (1 + \varepsilon) \\
\varepsilon_{\text{true}} &= \ln (1 + \varepsilon)
\end{align*}
\]  

(4)

where \(\sigma\) and \(\varepsilon\) are the engineering stress–strain values.

Figure 7. Two tensile test specimens: (a) the first tensile test specimen with dimensions and (b) the second tensile test specimen with dimensions.
Simultaneously, to analyze the variation of the mechanical properties and microstructure of the T-welded joint under different welding currents or heat input, and to investigate the effect of the welding defects on mechanical properties in detail, some measurements and sample preparations were conducted. For example, the specimens used for metallographic observation were cut by a wire-cutting machine tool from the joints perpendicular to the welding direction, and the cold inlay shall be carried out after wiping the specimens. After grinding and polishing, the specimens were etched in Keller reagent for 20–30 s. Afterwards, to clearly see the abovementioned welding defects and the distribution of chemical composition of the materials, the morphology and microstructure analyses on the obtained metallographic specimens were performed via optical microscope (OM) and scanning electron microscopy (SEM)/energy dispersive spectroscopy (EDS) examination. Furthermore, microhardness was measured using the SHIMADZU micro-Vickers hardness tester, under a 100 gf load force for 10 s, which is along the mid-thickness of the web plate and the base plate.

5. Results and Discussion

In this work, it has been clearly illustrated that the welding deformation and residual stress variation rules of T-joint thin-walled parts were carried out for different welding currents, as shown in Figures 5 and 6. From this foundation, the prepared tensile specimens and the T-welded joint under welding deformation were obtained to respectively analyze their tensile properties and the variation of the welding penetration depth.

5.1. Tensile Properties of T-Welded Joint

According to the tensile test results of T-welded joint specimens and Equation (4), the true stress–strain curves were determined as shown in Figure 9. Simultaneously, according to the true stress–strain curves, 0.2% offset strain was used to obtain the yield strength. Finally, the relative tensile mechanical properties of the T-welded joint were obtained, as shown in Table 2.

In Table 2, the specimens A-1 and A-2 denote, respectively, the first and second tensile test specimens when the welding current was 100 A. Moreover, the samples’ symbols corresponding with welding currents of 170 and 220 A have similar meanings as A-1 and A-2. It can be clearly seen from the ratio of the strength of the welded joint to the strength of BM that the yield strength and tensile strength were obviously lower than those of the base metal. To better investigate the reasons for this result, the metallography and microhardness measurement of the T-welded joint were carried out to analyze the microstructure morphology and microhardness variation.
5.2. Metallography

According to metallographic observation, the cross-section macrographs of two T-welded joints for each welding current were obtained using the stereoscopic optical microscope, as shown in Figure 10, and the specific welding penetration depth size was measured by ImageJ software. Moreover, the degree of lack of root penetration for the T-welded joint specimen was obviously visible. According to the abovementioned tensile results of the T-welded joint, the tensile properties and penetration depth curves with welding current variation are shown in Figure 11.

In Figure 10, due to the different welding currents, the heat input of TIG was also different, which affected the penetration depth and microstructure of the welded joint. Therefore, the weld penetration depth under different heat inputs was different. The weld penetration depth increased with the increment of the welding current overall. Moreover, the penetration depth generated by the welding current of 220 A was larger. However, the partial area of the welded joint was thoroughly welded, and there was an over-burning phenomenon. By comparing the results of welding penetration under three welding currents, the penetration depth was relatively appropriate when the welding current was 170 A. As seen in Figure 11, the tensile strength and yield strength also increased with the increment of the welding current to some extent. From this perspective, the penetration depth and tensile properties were greatly affected by the welding heat input.

Table 2. Mechanical properties of the T-welded joint.

| Welding Current | Samples | Yield Strength (MPa) (0.2% Offset Method) | Tensile Strength (MPa) | Percentage of Yield Strength | Percentage of Tensile Strength |
|-----------------|---------|------------------------------------------|------------------------|-------------------------------|-------------------------------|
| 100 A           | A-1     | 82.6                                     | 210.7                  | 29.9%                         | 67.8%                         |
|                 | A-2     | 91.9                                     | 215.2                  | 33.3%                         | 69.4%                         |
|                 | B-1     | 97.9                                     | 226.7                  | 35.5%                         | 73.1%                         |
| 170 A           | B-2     | 94.6                                     | 216.5                  | 34.3%                         | 69.8%                         |
|                 | C-1     | 100.9                                    | 218.4                  | 36.6%                         | 70.5%                         |
| 220 A           | C-2     | 98.6                                     | 215.9                  | 35.7%                         | 69.6%                         |
|                 | BM      | 276                                      | 310                    | —                             | —                             |

Figure 9. True stress–true strain curves for tensile test specimens: (a) stress–strain curve for the first specimen and (b) stress–strain curve for the second specimen.
Figure 10. Macrographs of the T-welded joint with penetration depth size: (a) 100 A-1, (b) 100 A-2, (c) 170 A-1, (d) 170 A-2, (e) 220 A-1, and (f) 220 A-2, where 100 A-1 and 100 A-2 denote, respectively, the welded joint specimens of two zones (numbered 1 and 2) cut by a certain distance on the T-joint thin-walled parts under a welding current of 100 A, and the other symbols are the same for 170 and 220 A.

Figure 11. Tensile properties and penetration depth curves with welding current variation.

Simultaneously, a metallographic observation was conducted by optical microscopy to obtain the microstructure features from the BM to WZ, as shown in Figure 12. Due to the existence of incomplete root penetration and the porosity defect of WZ and HZ, it is one of the reasons that the yield strength and tensile strength of the T-welded joint are lower than those of the base metal to a certain degree.
5.3. Welding Defects and Microstructure

Under conditions of a welding current of 100 and 170 A, the incomplete fusion defect, porosity defect, and grain boundary morphology of WZ and HAZ are shown in Figure 13. EDS elemental point analysis for WZ is shown in Figure 14, where the major energy peaks in each of the spectra were for aluminum, with minor peaks for magnesium, silicon, and titanium.

According to the microstructure features from the BM to WZ and welding defects of Figure 12, combined with Figure 13, it can be clearly seen that there were some welding defects, such as the incomplete fusion defect and porosity defect of WZ and HAZ, of the T-welded joint under welding currents of 100, 170, and 220 A. The welding defects were also very sensitive to the welding heat input, which had a great influence on the tensile properties. Especially, the porosity defect is an important influence factor on the tensile
strength of the weld. Stress concentration occurred at the porosity during the tensile test of the T-welded joint, which made the weld easier to fracture in the pore accumulation zone, resulting in a decrease of the weld strength. Simultaneously, as seen in Figure 12, the microstructure features for WZ and HAZ had some differences, mainly focused on the features of coarse and fine zones in the grain. The larger the heat input, the longer the grain stays at a higher welding temperature, which provides a condition for grain growth resulting in different grain sizes.

Figure 14. EDS elemental point analysis for WZ. (a) 100 A and (b) 170 A.

Figure 14 mainly analyzes the composition on the grain boundary near the weld zone and its defects. Although the welding heat input was different, the composition was not much different. Namely, the effect of the welding current had no great influence on its composition. However, the distribution of its components was affected to a certain degree.

5.4. Microhardness Measurements

According to the abovementioned T-welded joint specimens of macroscopic metallography, the microhardness measurement along A, B, and C directions, as shown in Figure 15, was carried out. The distance between key points on the cross-section center position of the T-welded joint in Figure 15 was 0.5 mm. The microhardness variation curve occurred at the position of WZ, HAZ, or near BM of macroscopic metallography of the T-welded joint.
In Figure 15a, for welding currents of 100, 170, and 220 A, minimum Vickers hardness values of 68.4, 56.3, and 71.3 were obtained at approximately 2, 3.5, and 7.5 mm along the A direction. Along the B direction, the minimum Vickers hardness values of 68.7, 55.2, and 55.2 were respectively located at about 3.5, 9, and 9.5 mm. In Figure 15b, minimum Vickers hardness values of 65.1, 50.1, and 62.4 were respectively obtained at approximately 2, 1, and 4 mm along the C direction for welding currents of 100, 170, and 220 A. These results show that the Vickers hardness value greatly changes for different welding currents or heat inputs, and the minimum hardness value occurred in the HAZ. Moreover, with a higher heat input, the Vickers hardness value and strength decreased in the HAZ.

According to the hardness variation curve in Figure 15, with the increase of the distance from the center O, the effect of the welding temperature on the grain decreased, and the hardness increased gradually until it was close to the hardness (100) of BM. The A side was firstly welded, and the B side was welded later for the T-joint thin-walled part structure. Therefore, the hardness of side A was higher than that of side B as a whole. This is the reason that the effect of the thermal temperature field on side B was stronger than that on side A. As well as its own thermal temperature field, the B zone is also subjected to the welding temperature of side A. Hereby, the measured hardness value on side B was relatively lower. In addition, the welding zone along the C direction was greatly affected by thermal coupling of A and B. With the increase of the welding current, the hardness value of C zone decreased compared to the BM hardness. According to the above analysis results, the fundamental reason that the hardness value was reduced is that the material softened with the increment of the welding current.

In this work, it is worth noting that the welding current can change the welding performance of the thin-walled structure, which is closely related to the welding heat input. Additionally, a larger or lesser welding current may lead to the degradation of the mechanical properties of T-welded joints, and the generation of an incomplete fusion defect and porosity defect, which may result in the failure in the service performance of welded joints for thin-walled parts. It is highly desirable and necessary to choose an optimal welding current or heat input and avoid the formation of welding defects in the TIG welded joint. It is proposed that the effect of the heat input level or the optimal welding process parameters’ combination, not just the welding current, should be further investigated during the welding process, through either the improvement of welding process behavior or the optimization of welding process parameters, together with appropriate use of welding clamping fixtures and joint constraint conditions, in the future. The results presented in this work can be useful in the actual welding process, which provides guidance for welding parameters’ optimization and quality assurance for the TIG welding process of thin-walled parts.
6. Conclusions

Based on the abovementioned results, it can be concluded that the effect of the welding heat input or different welding currents on the microstructure and the mechanical properties and welding defects of AA6061-T6 with ER4043 filler metal using TIG welding can be summarized as follows:

(1) The larger the welding current, the greater the warpage deformation for T-joint thin-walled parts, which is affected by the welding temperature field during the welding process to a great extent. However, the residual stress under the largest welding current was the smallest, compared to the other smaller welding currents. Therefore, the effect of the welding current or heat input on welding characteristics is relatively greater. Under these conditions, it is important to obtain a good T-welded joint for choosing a reasonable welding process parameter in the future.

(2) Considering the effect of the welding heat input on tensile properties, the yield strength and tensile strength of the T-welded joint increased with the increment of the welding current to some extent. For welding currents of 100, 170, and 220 A, the mean yield strength of the T-welded joint respectively accounted for about 31.6%, 34.9%, and 36.2% of BM strength, and the mean tensile strength respectively accounted for 68.6%, 71.5%, and 70.1% of BM strength. From this perspective, the yield and tensile strength decreased in both specimens of the T-welded joint. In particular, the yield strength of the T-welded joint significantly decreased. Meanwhile, due to the existence of incomplete root penetration and the porosity defect of the T-welded joint, the yield and tensile strength were lower than those of BM to a certain degree. The produced welding defect under different welding currents profoundly affected the tensile properties of the welded joint.

(3) The maximum penetration depth reached about 1.28, 1.81, and 2.18 mm, which respectively occurred at welding currents of 100, 170, and 220 A. That is, when the welding current or heat input increased, the penetration depth of the T-welded joint deepened, due to the melted volume of the welded joint materials caused by the increment of the welding heat input energy. Therefore, the penetration depth of the welded joint depends on the variation of the welding current. Correspondingly, the yield strength, tensile strength, and hardness value of the T-welded joint were nevertheless decreased overall.

(4) These welding process parameters, not just the welding current, including welding velocity, welding voltage, and other influence factors involving welding sequence, welding direction, heat source parameters, etc., should be comprehensively considered and optimized to obtain a reasonable weld penetration and tensile properties to satisfy the service requirements of thin-walled parts. Additionally, further works will also be concentrated on the response relationship among mechanical properties, penetration variation, and microstructure variation from a quantitative perspective, which will promote the mechanical properties of the T-welded joint and provide a theoretical basis for the actual welding process of thin-walled parts in the future.

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