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Numerical and experimental study for electron beam welding process of Al6061-T6 material

Gökhan Küçüktürk¹,* and Murat Atkaya²

¹ Department of Mechanical Engineering, Faculty of Engineering, Gazi University, Ankara 06500, Turkey
² Department of Mechanical Engineering, Graduate School of Natural and Applied Sciences Gazi University, Ankara 06500, Turkey
* Author to whom any correspondence should be addressed
E-mail: gkucukturk@gazi.edu.tr and murat.atkaya@gazi.edu.tr

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Abstract
Joining the aluminium 6061-T6 alloy (Al6061-T6) using Electron Beam Welding (EBW) was important, especially in aerospace. Although the EBW method has been used for different materials in the literature, there are a limited number of studies for Al6061-T6 alloy. The study aimed at the weldability and welding quality of 6061-T6 aluminium alloy plates by experimentally and numerically using the EBW technique. A numerical model has been generated to obtain the appropriate voltage, beam current, and welding speed parameters to simulate the EBW process instead of the hit and trial method, which is costly. The numerical model is based on a user-defined function based on the heat source as a function of temperature, welding parameters and material properties. The validation of the model has been compared by obtained width from numerical model and experimental work. Three EBW parameter sets were employed with the numerical model. Three different experimental parameter sets were determined according to the most suitable processing parameter that emerged from the numerical model, and experimental studies were carried out. Experimental studies showed defects in the microstructure due to process defects by unsuitable parameters. While the mechanical strength was 70% of the tensile strength performance compared to the main material, the elongation performance was 75%. The microhardness of the heat affected zone was measured as 84% of the base material, and a hardness reduction of 40% was also observed in the fusion zone. In addition, it showed that using the proper parameter set can eliminate such defects. The application of post-weld heat treatment procedures that can effectively improve the mechanical properties could be investigated in future studies.

1. Introduction
Aluminium alloys have found an area in significant amounts in the aeronautics, automotive and defence industries owing to their mechanical, physical and chemical properties and ease of production and processing methods [1–5]. Many methods can be used to manufacture parts from aluminium alloys; these can be listed as forming techniques, casting methods, machining and welding in general [6–11]. Welding methods can be classified according to engineering material processed: melting, solid-state and diffusion and are more practical and cheaper than other manufacturing methods. Fusion welding methods are widely used in welded joints of aluminium-based parts. However, in this method, adverse effects such as porosity, inclusions, cracks, strength reduction, insufficient bonding, heat-affected zone (HAZ), low corrosion resistance and low electrical resistance can be observed during the welding process [12]. If resistance, friction and diffusion welding methods are preferred from solid-state weldings, the listed negative effects of fusion welding methods can be avoided [13]. The Electron Beam Welding method (EBW) is classified as a fusion welding technique that can be joined by melting parts in an electron beam (EB) diameter area [14]. When the advantages of EBW are listed, energy efficiency, narrow and deep weld zone formation, high penetration, thin HAZ formation and application under
a controlled atmosphere are outstanding [14]. The main parameters in the EBW method are beam voltage, beam current (power), beam diameter, beam velocity and trace path. The determination of these parameters is an important topic. EBW application with improper parameters can cause deformities that seriously affect the joint quality. Elseddig et al. [15] investigated beam current, welding speed, sweep size, focus position on the mechanical strength of AA1350 aluminium. They emphasized the importance of parameter study in narrowing the HAZ and increasing the strength of the welding region; according to the experimental design, they applied EBW for AA1350 alloy, a material with low weldability. Nasr El-Deen et al. [16] focused on optimizing EBW parameters for AISI 304 stainless steel and AISI 1020 materials. As a result of the study, they reported that the energy of the beam current has a significant effect on the characteristic properties of the welded joint. Bardel et al. studied the estimation of residual stresses by microstructural analysis of the thermo–metallurgical approach using multiple physical models in the EBW of 6061-T6 alloy. Voltage and current parameters were used according to bench recommendations. Beam propagation velocity, mostly 0.45 m/min, formed the basis of experimental and numerical studies. They explained that the developed model measures the residual stress resulting from a single pass welding process [17]. Liu et al. generated a 3D numerical model for examining the melt pool during EBW of 2219 aluminium plate with 20 mm thickness. Their work considered three situations with different beam currents (35, 45, 65 mA). It has been suggested that evaporation increases with the beam current, a deeper weld melt zone is formed, but porosity is observed due to the vapour gaps [18]. Yang et al. investigated the multi–physics three-dimensional modelling of the melt pool. It has been determined that there is a correlation between the expansion of the electron beam diameter and the metal evaporation. Thus, they were verified experimentally and numerically with the Gaussian process regression (GPR) method [19]. In their study, Maisonnette et al. the mechanical behaviour of the sample, which was reduced to room temperature by raising the temperature at different heating rates during EBW of 6061-T6 aluminium alloy, was investigated. When they observed the microstructure with the Transmission Electron Microscope (TEM), they showed that the tensile strength of the HAZ region decreased due to the dissolution of the sediments in the alloy. The study was limited to the solidified HAZ region of the alloy [20]. Chen et al. The mechanical strength and microstructure of 3.5 mm thick EBWed Ti-22Al-25Nb alloy were investigated. It was stated that the conversion from the B2 phase to the α2 and O phases in FZ is limited due to the rapid cooling rate after EBW. They presented that the tensile strength ratio under the experimental condition ranged from about 91%. It was emphasized that the failed connections were either melted and solidified zone or in the HAZ [21]. In their study, Zhan et al. compared the 5A06 aluminium alloy samples processed by laser beam welding and EBW. They emphasized that the microstructure and mechanical properties of the EBWed joint is better than the joint welded by the laser beam [22]. Wang et al. examined the effect of heat treatment after welding application on 7055 aluminium alloy. They showed that the grain boundaries and continuous network structure that were evident after the heat treatments disappeared, and thus the mechanical properties of the welding region were also enhanced [23].

The study has proposed an approach to examining the weldability and welding quality of 6061-T6 aluminium alloy plates by the EBW method, guided by numerical simulations. In literature, the EBW process parameters have been chosen by machine producer catalogue rather than conducted study in scope of weldability and welding quality aspect. A numerical model based on EBW parameters, current, voltage and welding speed has been developed to conduct experimental studies. The experimental study was carried out with the results of numerical simulation of Al6061-T6 alloy evaluated within the scope of the study. Moreover, Al6061-T6 alloy based EBW included studies is narrowly wide.

2. Materials and methods

2.1. Numerical procedure

When the EB starts to weld the material, heat is transferred from the EB source to the Al6061-T6 material to simulate this heat transfer. The energy equation was used [24] as described by equation (1):

$$\rho C_p \frac{\partial T}{\partial t} = \nabla \cdot (k \nabla T) + Q(x, y, z, t)$$

(1)

Where, ρ, $C_p$, T and k is the density, specific heat, temperature and thermal conductivity, respectively. The material properties as a function of temperature were considered during the development of the model according to [25] and summarized in table 1. The EB heat source was assumed to have a Gaussian distribution profile according to [26, 27] and described as follows:

$$Q(x, y, z, t) = A \alpha \exp \left( - \frac{2 (x - v_x t)^2 + (y - v_y t)^2}{\omega^2} - \alpha z \right)$$

(2)

Where $A$ is the material absorptivity, $I_0$ is the heat source intensity, $\alpha$ is the effective absorption coefficient, and, $\omega$ is the characteristic radius of the EB source. The effective absorption coefficient depends on the material and...
heat source specifications and can be calculated according to Beer’s law. The absorptivity of Al6061-T6 is very high, and in this study, it was considered 100%[28]. The EB laser intensity can be calculated as follows:

\[ I_o = \frac{2(V \times I)}{\pi \omega^2} \]  
\[ \omega = \frac{D_h}{2 \times 2.146} \]

Where \( V \) is the welding voltage, \( I \) is the welding current, \( D_h \) is the EB diameter, respectively. The factor of 2.146 in equation (4) was estimated by considering the distance from the EB center (where \( I / I_o = 1/\epsilon^2 \)). By this way, the calculation of \( I_o \) can be accurately estimated using \( \omega \). It worth mentioning that both the initial and boundary conditions (equations (5) and (6)) were considered during the model development and are shown in figure 1.

\[ T(x, y, z)_{z=0} = T_0 \]
\[ -k \left( \frac{\partial T}{\partial z} \right) = S_h - h_{conv}(T_a - T) - \sigma \varepsilon (T^4 - T_s^4) \]

Where \( T_0, h_{conv}, T_a, T_s, \varepsilon \) are the intial temperature, the convection coefficient, the ambient temperature, the surrounding temperature, Stefan-Boltzmann constant, respectively. It is worth mentioning that the heat transfer by convection was considered. Although there was a vacuum condition, \( 10^{-4} \text{ mbar} \), used during the welding process allowing heat transfer by convection because of the lower vacuum pressure.

The simulation results used the enthalpy technique to control the melting and solidification contours. The enthalpy technique was formulated according to reference [24]. Enthalpy, which is the sum of the internal energy of the system and the product of the pressure and volume, can be defined as the sensible and latent heat
content as follows:

\[ H = U + P \cdot V \quad \text{or,} \]
\[ H = h + \Delta H \]

Where \( U \), \( P \), \( V \), \( H \), and \( \Delta H \) are the internal energy, the pressure, the change in volume, the sensible heat and the latent heat, respectively.

\[ h = h_{\text{ref}} + C_p \Delta T \]
\[ \Delta H = \beta L \]

Where \( h_{\text{ref}} \) is the reference enthalpy, \( L \) is the latent heat, \( C_p \) is the specific heat, and \( \beta \) is the liquid fraction. The fraction \( \beta \) can be calculated as follow:

\[ \beta = \frac{T - T_{\text{solidus}}}{T_{\text{liquidus}} - T_{\text{solidus}}} \]

The energy equation can be used to calculate the temperature \( T \), and then the liquid fraction \( \beta \) can be calculated using equation (11). According to the value of the liquid fraction \( \beta \), the state of the material can be defined according to equation (12) as follows:

\[
\beta = \begin{cases} 
<1 & \text{solid region} \\
\geq0 & \text{transition region} \\
>1 & \text{melting region}
\end{cases}
\]

ANSYS Fluent was used to solve the model equations described previously. A User Defined Function (UDF) contains the heat source, melting and solidification, the EBW parameters and material properties as a function of temperature, was developed and solved. The model geometry used in the analysis is shown in figure 2, and its
dimensions are according to ASTM E8/E8M-16a [30]. The model geometry consists of two identical parts to simulate the geometry used in the experimental setup.

The procedure for the numerical model solution steps is shown in figure 3. The finite element analysis software was used to generate the computational domain, established in figure 4. A few other regions of the model used very fine discretization for the welding path part. Mesh density analysis (grid independence test) was carried out to ensure that the obtained results from the model due to poor mesh quality were avoided. Therefore, four different mesh sizes were evaluated and tested. The result for the mesh density analysis was shown in figure 5, where the welding width was used in this comparison. The mesh with an edge size of 100 μm gives a width size of 3.818 mm. When the mesh edge sizing was reduced to 75 μm, the welding width was reduced to 3.7 mm, which can be considered a significant effect for the mesh size—lowering the mesh edge sizing to 50 μm, the welding depth by 0.02 mm (3.68 mm), comparing the width obtained using the 75 μm mesh edge sizing. Another refinement in the mesh was considered where a mesh edge sizing of 40 μm was studied, and the obtained welding width was 3.67 mm. Since the mesh edge sizing of 50 μm gave a very close result than the mesh edge sizing of 40 μm (the error between the two results is 0.27%), the mesh edge sizing of 50 μm was used in this study.

2.2. Experimental
2.2.1. Specimen preparation
A 6 mm thick aluminum 6061-T6 plate was used to prepare the tensile specimen according to ASTM E8/E8M-16a [27], as can be seen in figure 6, and the specimen was cut into two identical parts as described in section 2.1.
2.2.2. Electron beam welding

The EBW process of Al6061-T6 was performed on an EBW machine (Steigerwald 175 kV max. voltage), and the process atmosphere was kept in vacuum conditions about 10^{-4} mbar by a turbo molecular pump. The specimen was fixed in the machine table using a fixture tool, as shown in figure 7(a). With the help of fixtures, metal plates are placed in front of and behind the welding line (figure 7(b)). In the experiments, the welding line was kept longer than required to ensure a steady beam effect was obtained along the weld line on the sample region. Thus, the adverse effects that may occur due to the sudden interaction of the beam and the sample are prevented.

2.2.3. Characterization

The numerical model’s recommended values for the process parameters were used for welding Al 6061-T6 material. Tests were carried out depending on three different parameter sets determined after the numerical analysis. Sample thicknesses were selected as 6 mm. After the sample surfaces were prepared mechanically and chemically for EBW, applied butt welding collinearly to the rolling direction. Radiography, microhardness, and tensile tests were applied to the samples to evaluate the welded joint and to see the effect of EBW process parameters. The radiography test was used to examine the welding gaps in the welded specimens and was carried out using Bauartkennzeichen Bfs 01/04R manufactured by GE Sensing & Inspection Technologies. The microstructural changes occurring in the samples’ HAZ and fusion zone (FZ) were comprehensively observed by LEICA DM 4000M model optical microscopy, Jeol JEM 6060 LV model scanning electron microscopy (SEM) and elemental EDX analysis. Samples were etched with Keller’s etching solution for the optical microscope. In addition, to understand the hardness of the HAZ, the hardness values were measured using the Emco-Test Hardness device for three parameter sets. Microhardness tests were carried out from the weld metal to the BM at HV 0.5 from the weld zone. Additionally, a tensile test was applied to determine mechanical properties and...
performance: yield stress, ultimate strength, elastic modulus, and elongation. The tensile tests were carried out according to ASTM E8/E8M standards using INSTRON 5985 test machine.

3. Results and discussion

3.1. Model validation
To validate the developed numerical model and confirm the results obtained from the numerical model with the experimental results, model validation was carried out. For this purpose, the size of the melted zone width obtained numerically was compared with the one obtained experimentally, as shown in figure 8. The results showed that both results (Numerical and experimental) are very close, with a maximum error of 11.7%. This error value is accepted, and the validation of the numerical model was confirmed. At this stage, the numerical model can be effectively used to obtain the proper process parameters of the EBW process.

3.2. Numerical results
The numerical model was used to investigate the process parameters (the welding voltage, current, and speed) to determine the working limit of these parameters in the experimental study. The investigation for the process parameters was based on two criteria: Firstly, the process parameters have to melt the total thickness of the specimens (6 mm). Secondly, no evaporation (the working temperature should be less than 2000 K) must not happen for the Al 6061-T6 due to high input heat. To make this investigation, the voltage and the welding speed were fixed at three different values, and the model was used to determine the values of the welding current that can meet the above two criteria. The welding voltages used are 60, 57, and 54 kV, while 33, 30, and 27 mm s$^{-1}$ were used for welding velocities. For the 60 kV and welding speed 27 mm s$^{-1}$, as shown in table 2, using a current value of 35 mA could penetrate the total thickness of the plate, however, with a narrow welding depth at the bottom, which should be avoided and is not recommended. The welding depth at the base increased as increasing the current to 40 mA. Increasing the current to 42 mA gave a maximum temperature very close to 2000 K, leading to evaporation of the material from the top surface. Therefore, it is recommended to use 40 mA with 60 kV and 27 mm s$^{-1}$. The same procedure was followed to determine the welding current values at different currents and speeds, and the results were summarized in table 3.

3.3. Experimental results

3.3.1. Radiography analysis
Specimens were welded for each parameter set. Figure 9 shows the radiography analysis results for specimens of the three different parameters set. There is a wide gap at the welding plane for set A, and some of the specimens were not completely connected. This is mainly because of the high inertia effect of EB due to the high-Intensity Energy (IE) input. IE calculated by voltage × current / scanning speed (kJ/m) for this set is 88.8 kJ/m. This IE led to the specimens’ sudden thermal expansion and made it bend, as shown in figure 9(a), which led to the separation at the welding plane before solidification. Set B has an IE of 84 kJ m$^{-1}$, which is between the IE for Set A and C, and succeeded in avoiding the previous problem in Set A and C, as shown in figure 9. Set C gave the same behaviour but with a narrow gap, and this is because Set C has a low IE value (80 kJ m$^{-1}$) that made it unable to melt the whole depth of the specimen.
3.3.2. Microstructure

Optical microscope and SEM images of the welding region were taken from the Set A, Set B, and Set C parameters samples. Due to the production conditions of the material, such as chemical pretreatment or rolling, defects may be seen in the weld area after welding. Because of its nature, the EBW technique is performed under a vacuum so that these defects can be more minor. However, possible process defects may still occur due to inappropriate parameters (figure 10) [31].

Solidification cracks generally occur in the FZ and are mainly caused by the lack of molten metal needed to fill the areas stressed by thermal contraction. It is possible to eliminate such defects if the correct parameters are selected. These cracks are seen from an SEM image after welding obtained with Set A and Set C parameters (figures 10(a) and (b)). As a result of the Set B parameter, which was determined as the best welding parameter, solidification cracking was not observed in the weld zone (figure 11).

| Set | Process parameters | kV | mA | mm/s |
|-----|-------------------|----|----|------|
| A   | 60                | 40 | 27 |
| B   | 60                | 42 | 30 |
| C   | 60                | 44 | 33 |

Table 3. The recommended values from the numerical model used in the experimental analysis.
Due to the nature of EBW, by applying high welding speed and intense energy in a narrow space, it is seen that typical microstructures close to the cast form are occurred by the fast cooling of the molten material. Figure 12 shows the optical microscope photograph of the region where FZ, HAZ, and BM coexist after welding with Set B. Unlike the BM microstructure, coaxial crystals were observed in the FZ and cellular dendritic structures near the fusion lines and the HAZ due to varying degrees of thermal gradients with the cooling process. These cellular dendritic structures are very thin compared to other traditional welding methods because of the higher cooling rate in the welding region. In addition, while liquidation cracking is seen intensely in conventional welding methods, it is also present in the EBW method, albeit a little. When the BM region is examined, it is seen that there are Mg$_2$Si precipitates formed after ageing (figures 13(a)–(c)) [33]. While Mg$_2$Si is frequently found in the BM, it is not seen in the FZ region and less in the HAZ region. The reason why the precipitates of Mg$_2$Si are not seen in the HAZ and the FZ can be associated with the evaporation of Mg as a result of high-intensity heat [34]. Instead, it was considered that Al-Si eutectic structures were concentrated more in FZ, and these eutectic structures were formed by condensation in FZ. The Al-Si eutectic structure has a low melting point and can be found as aggregates between $\alpha$-Al grains (figure 13(b)). In table 4, where EDS results are presented, it is seen that the Si found more in FZ and Mg decreased compared to BM [35].

3.3.3. Microhardness test

Hardness measurements in the welded condition were made within 10 h of the welding process. After the sample was welded with parameter sets A, B, and C, hardness measurements were made at regular intervals from the...
centre of the FZ to the base material with 0.5 HV. As a result of the measurements, a softening occurred in the FZ centre region to approximately 1.5 mm (figure 14). The hardness reduction is caused by the dispersion of Mg2Si sediment formed due to ageing by heat input [34]. Microhardness increases from the HAZ region towards the BM. It is suggested that a solution annealing treatment should be performed to restore the hardness [36].

Additionally, the microhardness measurement was used to evaluate the hardness on a vertical cross-section perpendicular to the welding path, which was used to correlate numerical analysis and experimental studies. Figure 15 shows the measurements path around the molten material. For the bar material, the hardness is 88.5 HV, while for the welded specimen, there are variations in the measurements at the different points. This variation is mainly due to the non-uniform distribution of the temperature. It can be concluded that post-processing operations are needed to make the hardness uniform, which will help enhance the mechanical performance.

### 3.3.4. Tension test

According to ASTM E8/E8M standards, the tension test was carried out using INSTRON 5985 test machine. The tensile strength performance of the EBWed specimen was determined and compared between Set B and unwelded bar material. Set B was chosen for comparison as it did not show any defects in the radiography analysis and SEM results. Figure 16 shows the stress-strain curve for Set B and the bar material specimen. There is a mechanical performance gap between the bar material and the welded sample.
The bar material’s yield stress, ultimate strength, and elastic modulus are 288.91 MPa, 317.31 MPa, and 86.08 GPa. At the same time, those values are 172.31 MPa, 224.89 MPa, and 32.46 GPa for Set B. At the same time, those values are 172.31 MPa, 224.89 MPa, and 32.46 GPa for Set B. The performance for tensile strength was ~70%, while the performance for elongation was deficient, ~25%.

In Set B samples, it was observed that the FZ was fractured from the weld due to hardness and microstructure changes. Due to the significantly lower loss of stiffness of the Al 6061 T6 welded joint, its ductility has also decreased. As expected from the hardness profiles, Al 6061 –T6 also showed significant ductility losses due to the

| Table 4. Chemical compositions of the material observed in different regions of Al6061-T6. |
|----------------------------------|--------|--------|--------|--------|--------|--------|
| 1-HAZ   | Bal.  | 1.292  | 1.304  | 0.719  | —      | 0.408  | 0.198  |
| 2-FZ    | Bal.  | 0.772  | 0.848  | 0.272  | —      | 1.134  | 0.247  |
| 3-BM    | Bal.  | 0.946  | 1.143  | 1.137  | —      | 0.698  | —      |

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strain concentration in the low strength narrow FZ. The strength of aluminium alloys is obtained from solid solution strengthening or precipitation hardening of Mg2Si. The reduction of alloying elements leads to a decrease in the strength of the melt and resolidify zone. Therefore, fracture occurs with stress concentration in the welded region of low-strength welded joints. Also, lower ductility levels are seen in the welding region.

Figure 15. Hardness measurement around the welded material.

Figure 16. The stress-strain curves for the main material and Set B sample.

Figure 17. Welded specimen using parameter Set B: (a) as-welded specimen, (b) specimen after tension test.
Additionally, the low performance of the EBW specimen is mainly due to the high welding speed of the EB and the high IE of the EB that led to the cross-section area reduction at the welding plane, as seen in figure 17. In addition, the absence of filler material between the parts to be welded in these welding processes can be considered another reason. Therefore, the surrounding material around the welding plane is used as a filling material and reduces the cross-section at the welding plane.

4. Conclusions

The EBW of Al 6061-T6 has been investigated numerically and experimentally. The different IEs used in this study did not affect the weld penetration but did affect the mechanical properties of the weld due to defects. The developed numerical model can be used effectively to determine initial parameter values that guide the experimental analysis. In this way, possible welding defects can be minimized.

The tension test showed that the optimised parameter set’s welded material gave low mechanical performance than the bar material specimen. The low mechanical performance of the welded specimens is due to the change of material composition in the weld zone due to the high inertia and IE of the EB, the evolution of different microstructures such as dendritic and coaxial crystal, and the reduction in cross-sectional area. This low-performance effect decreased ductility due to the significantly lower hardness loss of the Al 6061-T6 welded joint. In Set B, the hardness values were decreased in HAZ and FZ, 16% and 40%, respectively. The welding performance in tensile strength slightly changed, while the performance for elongation significantly decreased. The tensile strength obtained 70% of BM, and the elongation performance was 75% of BM. For Set B, the yield stress, ultimate strength, and elastic modulus are 288.91 MPa, 317.31 MPa, and 86.08 GPa, respectively, which is the best results.

Post-processing operations are needed to enhance the welded specimens’ mechanical properties for future prospects.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

Data accessibility

All data related to this research are contained in the manuscript.

Conflicts of interest

The authors declare no conflict of interest

ORCID iDs

Gökhan Küçüktürk © https://orcid.org/0000-0002-2978-8968
Murat Atkaya © https://orcid.org/0000-0001-5619-3858

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