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Microstructure and magnesium burning loss behavior of AA6061 electron beam welding joints

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Full penetration butt welding with different parameters was performed on 4 mm thick AA6061 plates. The microstructural characteristics, element burning loss behavior and their effects on the mechanical properties of the weld beams were studied. It revealed that the weld porosity could be effectively controlled with a lower welding velocity and the crystal enlargement is rather obvious near the weld upper surface. The secondary-precipitated phase AlFeSi was observed at the crystal boundaries, whereas the strengthening phase Mg_2Si within the welds is undetectable by SEM. The magnesium burning loss behavior of the welds embodies in two aspects: the decrease in magnesium content compared to the original alloy and the uneven distribution of magnesium with a decrease tendency as close to the weld surface and a symmetric growth as further away from the seam center line. The welded joints with a higher burning loss degree of magnesium are performed at a lower Vickers hardness, tensile strength, plasticity and toughness. The characteristic isotherm and convection within the molten pool during EBW were considered as the key factors that dominated the microstructure and magnesium distribution.

1. Introduction

Aluminum alloy 6061 has been generally considered as a valuable structural material with extensive application in aerospace, transportation and architecture fields since its discovery [1,2]. As a typical kind among the Al–Mg–Si series alloy, the performance of 6061 relies heavily on 0.8–1.2% magnesium and 0.4–0.8% silicon containing (wt.%), resulting in comparatively good mechanical properties, formability and weldability [3].

Welding of aluminum alloy has long been challenging but quite active. Arc welding has been commonly employed for AA 6061 joining in industries for years. However, it brings significant deformation and metallurgical reaction (resulting in crack, porosity, grain coarsening, alloy elements burning loss, e.g.) due to high heat input and low welding speed [4,5]. Effective improvements in these issues can be obtained by using high energy beam welding methods, such as laser beam welding (LBW) and electron beam welding (EBW).

One sign of increasing maturity in LBW is the successful development high power laser (HPL). Laser welding for aluminum alloys now has finds its way into much more extensive industrial applications and become relative ease for development compared with EBW, due to the high welding velocity, operating flexibility accompanied by deep penetration, minor distortion and fine grains [6–8]. Nevertheless, EBW actually has been confirmed over time to be more energy conversion efficient than LBW, which still suffers from low photoelectric efficiency itself and initial high reflectivity of aluminum alloy against laser beam [9]. Other advantages including contamination free and effective removal of oxide make EBW a relatively ideal method for welding aluminum without considering the production cost.

Considerable studies on electron beam welding of aluminum alloy [10–21] have been reported where process parameters, weld formation, properties, microstructure, defects and numerical simulation were discussed, but few of them were related to AA6061. Strombeck [22] studied electron beam welding of AA6061 where the local microstructure–property relationships and the effect of strength mismatch were analyzed. In [23], EBW was used for cold pates joining made from AA 6061 T851 to minimize the distortion and maximize the penetration depth and by which the residual welding stress was controlled. In addition, Dahan [24] and Huang [25] focused on the joining of AA6061 with dissimilar materials.

To obtain an in-depth understanding of EBW for AA6061, more comprehensive and profound efforts on welding parameter matching and joint quality, melting mechanism, metallurgy process and defect generation mechanism are supposed to be made. Among these points, the microstructure and the distribution of alloying elements in welds are fundamental but quite important since their tight correlations with the temperature field, molten convection and element evaporation during welding processes and the welded joint mechanical properties.

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Table 1
Chemical composition of AA 6061.

Element	Mg	Si	Fe	Cu	Mn	Cr	Zn	Ti	Al
wt.%	1.08	0.53	0.38	0.31	0.043	0.17	0.016	0.033	Bal

Table 2
Different sets of parameters in AA6061 electron beam welding.

Experimental case	Accelerating voltage *U* (kV)	Electron beam current *I* (mA)	Welding speed *v* ($m \cdot min^{-1}$)	Heat input *Q* ($J \cdot min \cdot m^{-1}$)
1	22	65	1	1430
2	22	50	0.5	2200

Partly related investigations have been performed in previous studies on laser welding or laser-arc hybrid welding for AA6061 that are worth considering [26–32].

In the current study, AA6061 T6 plates were electron beam welded. Welding parameters are optimized for desired weld surface formation quality. The microstructure of critical regions including heat affected zone (HAZ), fusion zone (FZ), defects and strengthening phase of the joint were investigated. Elemental distribution and phase composition were qualitatively and quantitatively analyzed. The burning loss behavior of magnesium and the mechanism were explored. Besides, the influence of magnesium evaporation loss on mechanical properties was verified using the micro hardness as well as tensile strength of welded joints.

2. Experimental details

Aluminum alloy 6061 T6 (treated by solid solution at 530 °C for 4 h and then artificial aging at 160 °C for 18 h) plates with the dimension of $100 \times 50 \times 4$ mm^3 were used as the welding base. Butt electron beam penetration welding experiments without wire filling were conducted using GENOVA98 with a vacuum degree of 7×10^{-4} mbar. The chemical composition of AA6061 is shown in Table 1.

The welding direction is parallel to the rolling direction of AA6061 plates. The processing parameters of EBW including accelerating voltage, electron beam current and welding speed were tested in advance and preliminary optimized. The function shape of circle and a scanning frequency of 1000 Hz were adopted as the common parameters of EB. Different sets of parameters were applied and divided into 2 cases (Table 2).

Surface clean-up treatment for the metal base prior to welding is indispensable for obtaining a high welding quality. The processes involve mechanically abrading, acid pickling and acetone cleaning.

After welding, the macro performance of the welds was captured by CCD camera. The weldments were then machined into specimens for the measurements of microstructure (specimen A) and mechanical properties (specimen B1–B3). The exact sampling locations and related dimensions are shown in Fig. 1.

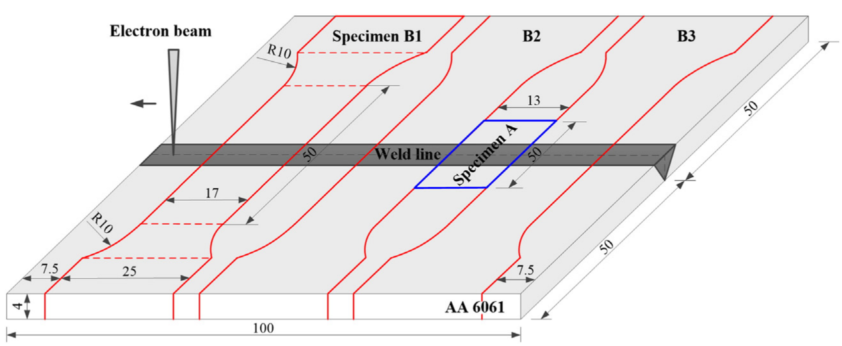

Fig. 1. Sampling locations and dimensions on AA6061 weldment in mm.

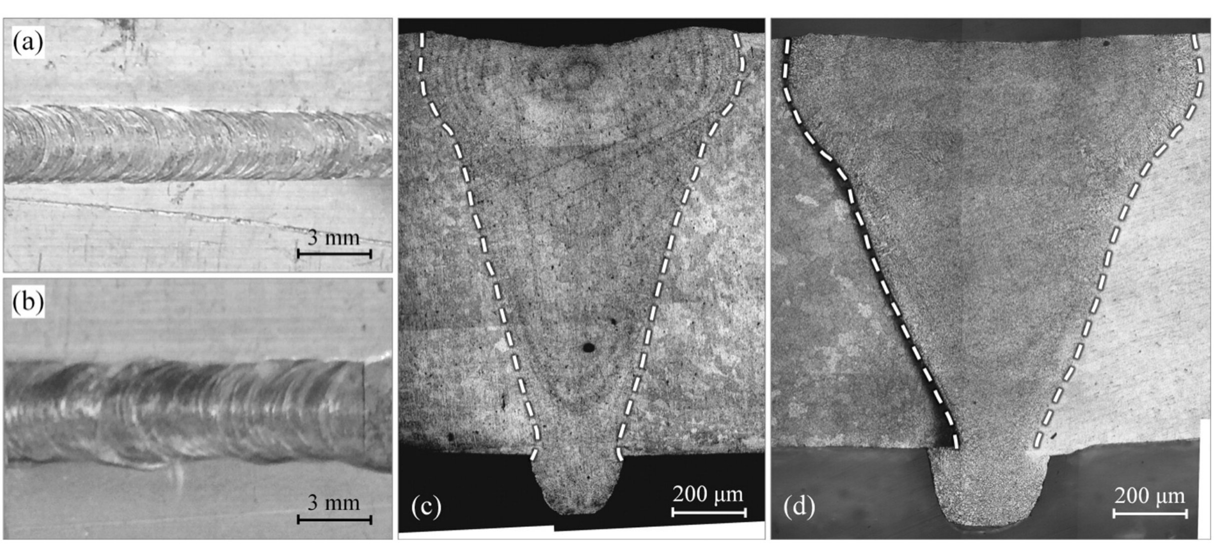

Fig. 2. Macroscopic appearance of surface and cross section of AA 6061 welds by EB: a) case 1, surface formation; b) case 2, surface formation; c) case 1, cross section; d) case 2, cross section.