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Microstructural development of electron beam processed Al-3Ti-1Sc alloy under different electron beam scanning speeds

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ABSTRACT

A systematic study has been made of the microstructural development in as-cast 30 mm thick Al-3Ti-1Sc (wt%) plate samples that were processed by electron beam (EB) melting at different scanning speeds of 3, 5, 8, 12, 15 and 20 mm/s. The composition of the alloy is designed to capitalize on the potential for significantly extended solubility values of both Sc and Ti in Al when cooled at high cooling rates. The resulting microstructures are characterised using transmission electron microscopy (TEM) and other analytical means, assisted with Thermo-Calc predictions and Vicker's microhardness measurements. EB scanning speed plays a key role in determining the phase formation and microstructural development in the Al-3Ti-1Sc alloy when the beam is applied an accelerating voltage of 50 kV and a current of 30 μA. The major microstructural features in the re-solidified zone include (i) the formation of the primary tetragonal Al_3(Ti,Sc) phases and their retention or subsequent transformation to stable cubic Al_3(Ti,Sc) phases; (ii) the complete suppression of the primary tetragonal Al_3(Ti,Sc) phases at the scanning speed of 20 mm/s; and (iii) the formation of cubic Al_3(Ti,Sc) precipitates in the α(Al) matrix supersaturated with both Sc and Ti. These experimental findings are informative for both EB processing of Al-Ti-Sc alloys and the design of new Al alloys for additive manufacturing processes.

1. Introduction

Wire-based electron beam additive manufacturing (EBAM) is a novel metal additive manufacturing process developed for advanced aerospace applications in the early 2000s by Sciaky, Inc. with assistance from Lockheed Martin and NASA Langley Research Centre [1–3]. The process uses a focused electron beam as the heat source to melt a wire form of feed stock material and deposit it on a substrate layer-by-layer to fabricate three-dimensional (3D) structural parts. In each layer, the depositing pattern is precisely controlled by computer instructions from a CAD model to realize the layer additive manufacturing process. Compared to laser based additive manufacturing (AM) processes, EBAM has several attributes [4]: (i) Gross deposition rates can reach up to 15 kg of metal per hour, and the process can be used to produce large-scale metal structures as large as the processing chamber allows. (ii) The electron beam (EB) process is inherently power efficient, on the order of magnitude of 90% or better, while the power efficiency of a laser process is typically much lower. (iii) Electron beam couples well with most metals; it is therefore better suited to fabricating materials which are difficult to couple with laser, such as Al and its alloys whose reflectance to laser beam energy at room temperature can be as high as 95% [5]. (iv) The EB process operates in a vacuum environment, which minimizes oxygen pick-up and ensures the chemical integrity of the processed material [6–8].

As with other metal AM processes, the EB-melted material solidifies under conditions far from equilibrium cooling during EBAM. This provides an opportunity for new alloy designs which can take advantage of the fast cooling of the EBAM process, for example, the increased solubility for subsequent precipitation hardening. Scandium (Sc) is a light but highly potent strengthening alloying element for Al with an approximate maximum solubility of 0.35 wt% at 928 K (655 °C). In a typical as-cast Sc-containing Al alloy, Sc forms fine Al_3Sc precipitates with Al imparting good creep resistance to the alloy up to 573 K (300 °C) due to precipitation strengthening [9,10]. Recently researchers have also found that these Al_3Sc precipitates can be further stabilized by introducing Ti and Zr [11–14], which can substitute up to

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50% of Sc atoms in the Al_3Sc intermetallic lattice [15] but have much slower diffusivity in Al than Sc. For example, quaternary AlMgScZr alloys were developed to benefit from the precipitation hardening effect of $Al_3(Sc + Zr)$ [16,17]. In addition, ternary Al-Sc-Ti and Al-Sc-Zr master alloys have been developed to assist in alloy developments [18]. However, the amount of Sc that can be precipitated for hardening in the Al matrix is rather limited because of its small solubility in Al when processed by a typical casting process with a relatively slow cooling rate. Recent research by the authors on an Al-2Sc (wt%) alloy shows that this problem can be mitigated by EB processing which can substantially increase the solubility of Sc in α(Al) and doubles the hardening effect compared to conventional solid solution and aging [19]. In this prior research on Al-2Sc [19], the EB scanning speed, which is an important processing parameter for EBAM, was fixed at 10 mm/s. On the other hand, ternary Al-Ti-Sc alloys have the potential to offer novel or improved microstructures compared to binary Al-Sc alloys. The purpose of this research is to systematically assess the microstructural development of a newly designed ternary Al-3Ti-1Sc (wt%) alloy for maximum precipitation hardening when processed by EB under different conditions. The experimental data produced provide new perspectives on the microstructural development of Al-Ti-Sc alloys by EB processing.

2. Experimental Procedure

The electron beam processing is illustrated in Fig. 1. The substrate material used was a 30 mm thick and 200 mm square casting plate of Al-3Ti-1Sc (wt%), solidified in a steel mould. The design of the alloy composition will be discussed subsequently. Cuboidal samples with dimensions of 200 mm (length) × 50 mm (width) × 30 mm (thickness) were machined from the casting plate and processed with an EB gun in a vacuum of 10^{-3} Pa at 50 kV with a fixed beam current of 30 mA. Five re-melt passes were created with different scanning speeds (mm/s) of 3, 5, 8, 12, 15 and 20. The processed samples were cut perpendicularly to the EB re-melt lines to reveal the profile of the resolidified pool. An X-Ray diffractometer (XRD) with Cu Kα radiation was used for phase analysis of the EB re-melted zone. A Struers Duramin A-300 Vickers microhardness tester was used for hardness measurement with a load of 100 g and duration of 12 s in 200 μm steps. A Polyvar optical microscope (OM) and a Philips XL 30 scanning electron microscope (SEM) were used for microstructure observation. The microstructures were further investigated using a Tecnai F20 transmission electron microscope (TEM) equipped with Energy-dispersive X-ray spectroscopy (EDS). Thermo-Calc Software and its Al database TCAL2.1.1 were used to assist in alloy designs.

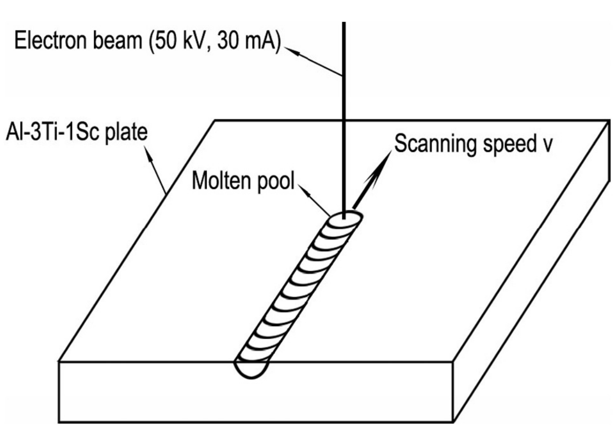

Fig. 1. Schematic illustration of the electron beam processing of the Al-3Ti-1Sc alloy plate.

3. Experimental Results

The composition of the Al-3Ti-1Sc (wt%) alloy is designed based on the following considerations. Fig. 2 (a) shows the equilibrium Al-Ti phase diagram up to 5 wt%Ti, which involves a peritectic reaction at ~937 K (664 °C). When a molten Al-Ti alloy cools down at a slow cooling rate, primary phase Al_3Ti first forms in the liquid until it reaches the peritectic temperature, at which point the primary phase reacts with the liquid phase to form α(Al) solid solution. The solubility of Ti in α(Al) decreases quickly with decreasing temperature. Therefore, there will be precipitation of intermetallic Al_3Ti particles in α(Al) during subsequent cooling. In contrast, if the liquid alloy cools down at a sufficiently high cooling rate, the solidification path will be completely different. Fig. 2 (b) shows a metastable Al-Ti phase diagram predicted using Thermo-Calc software. Both the primary phase Al_3Ti and the peritectic transformation predicted by the equilibrium phase diagram are suppressed and absent from the metastable Al-Ti phase diagram. As a result, the solubility of Ti in α(Al) can be increased substantially. For example, at about 943 K (670 °C), the solubility of Ti in α(Al) can reach about 3 wt% compared to the maximum solubility of about 1.2 wt% at 937 K (664 °C) under equilibrium conditions, Fig. 2 (a). The Al-Sc and Al-Ti phase diagrams are similar at their Al-rich ends. The metastable Al-Sc phase diagram predicted by Thermo-Calc also resembles the Al-Ti phase diagram in Fig. 2 (b). A recent study by the authors revealed that the solubility of Sc in α(Al) can be tripled from

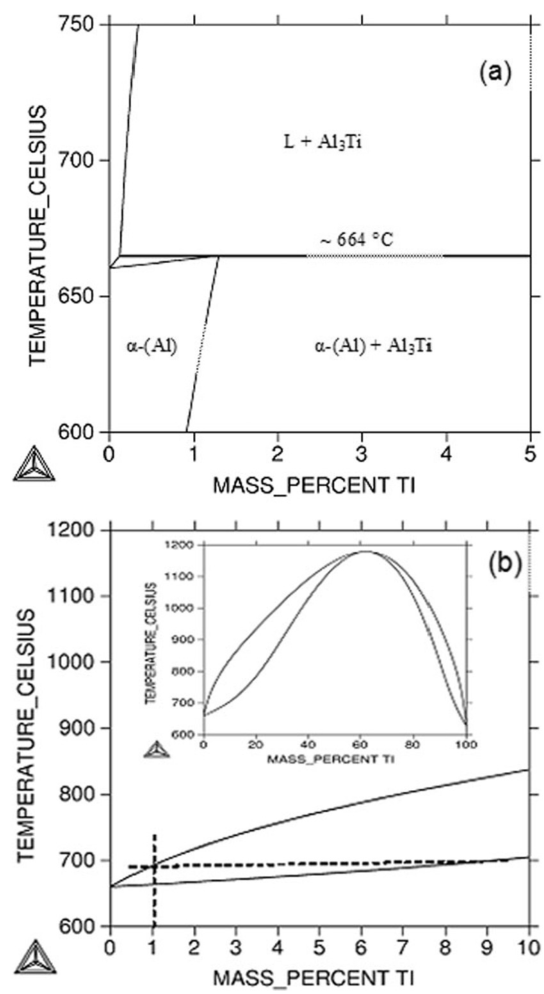

Fig. 2. (a) A portion of the Al—Ti equilibrium phase diagram up to 5 wt%Ti showing a peritectic reaction at 937 K (664 °C) and (b) a portion of the metastable phase diagram of the Al—Ti system in the range of 0–10 wt%Ti constructed by suppressing the nucleation of the pre-peritectic Al_3Ti. The inset in (b) is the complete metastable phase diagram.