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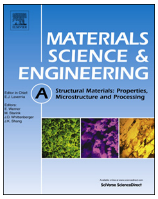

The effect of location on the microstructure and mechanical properties of titanium aluminides produced by additive layer manufacturing using in-situ alloying and gas tungsten arc welding

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ABSTRACT

An innovative and low cost additive layer manufacturing (ALM) process is used to produce γ-TiAl based alloy wall components. Gas tungsten arc welding (GTAW) provides the heat source for this new approach, combined with in-situ alloying through separate feeding of commercially pure Ti and Al wires into the weld pool. This paper investigates the morphology, microstructure and mechanical properties of the additively manufactured TiAl material, and how these are affected by the location within the manufactured component. The typical additively layer manufactured morphology exhibits epitaxial growth of columnar grains and several layer bands. The fabricated γ-TiAl based alloy consists of comparatively large α_2 grains in the near-substrate region, fully lamellar colonies with various sizes and interdendritic γ structure in the intermediate layer bands, followed by fine dendrites and interdendritic γ phases in the top region. Microhardness measurements and tensile testing results indicated relatively homogeneous mechanical characteristics throughout the deposited material. The exception to this homogeneity occurs in the near-substrate region immediately adjacent to the pure Ti substrate used in these experiments, where the alloying process is not as well controlled as in the higher regions. The tensile properties are also different for the vertical (build) direction and horizontal (travel) direction because of the differing microstructure in each direction. The microstructure variation and strengthening mechanisms resulting from the new manufacturing approach are analysed in detail. The results demonstrate the potential to produce full density titanium aluminide components directly using the new additive layer manufacturing method.

1. Introduction

Titanium aluminide alloys based on intermetallic γ phase are widely recognised as promising structural materials due to their attractive combination of low density, unique mechanical properties such as high specific strengths and moduli, and good resistance against oxidation and corrosion [1]. These properties make γ-TiAl alloys attractive for high temperature aerospace and automotive components such as turbine wheels, compressor blades and pistons for reciprocating engines [2].

Despite the desirable characteristics of these alloys, TiAl components are difficult to manufacture by conventional production processes due to relatively low ductility at room temperature. Another drawback is the high processing temperature, owing to the long-range ordering of TiAl up to its melting point. Greater capital investment is required for processing equipment with the necessary high temperature characteristics [3]. Industrial scale processing routes that have been used to produce γ-TiAl alloy billets and components include investment casting, ingot or powder metallurgy. These techniques are similarly applied to conventional titanium and nickel based alloys. However, for the case of TiAl alloys, these processes often require a series of additional post-processing steps such as hot-isostatic pressing, ageing, annealing, and hot working to improve the mechanical properties to desirable levels and to obtain the desired component geometries. For casting and ingot metallurgy processes, the main difficulties encountered in producing γ-TiAl are the development of cracks, inhomogeneous microstructure and coarse-grained microstructure, resulting in poor mechanical properties. For example, casting defects and strong segregation of impurity elements are found in titanium aluminides produced by various casting methods [4]. Bryant and Semiatin [5] have pointed out that microsegregation is an obvious phenomenon in multicomponent ingot-metallurgy titanium aluminides as well as in binary alloys. Powder metallurgy minimises these problems, but introduces the likelihood of porosity and contamination [6]. Although post-processing operations can solve many of the problems associated with the three main processes, and

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each process can produce acceptable material, the overall production costs are inevitably increased. High costs have been acknowledged as the chief limitation for titanium aluminides to successfully reach the market in a wide range of part forms.

Efforts have been devoted to explore alternative manufacturing techniques for titanium aluminides, such as direct rolling, laser forming and sintering [7]. Although these techniques are capable of producing material with acceptable properties, processing costs and product shapes are still prohibitive for many commercial applications.

It is well known that joining techniques play an important role in the application of γ-TiAl based alloys. Processes that have been used for joining gamma titanium aluminides include fusion welding (electron beam welding and gas tungsten arc welding), solid state welding and brazing. Considering its high deposition rate and low cost, gas tungsten arc welding is an appealing option for investigating novel fabrication technology based on the study by Wang et al. [8].

Additive layer manufacturing (ALM) has been shown to be a feasible and economical alternative to traditional manufacturing methods for conventional metals. Many consecutive layers are deposited onto a substrate using powder or wire to produce complex, near net shape components. Thus, ALM has the potential to produce geometrically intricate components with major savings in time, material, and hence cost.

Considerable investigation and development have been carried out on ALM processes applied to conventional metals, ranging from aluminium [9,10], nickel [11,12], steel [13] and titanium alloys such as Ti–6Al–4V [14–18]. In comparison, the application of ALM to intermetallics such as titanium aluminide has been limited. Srivastava [19,20] applied direct laser fabrication to fabricate TiAl alloy components using gas atomised TiAl powders. The range of processing parameters was identified and controlled by an intelligent feedback system. The authors also established the relationship of processing parameters and the subsequent heat treatment with the microstructure and mechanical properties. Laser melting deposition (LMD) ALM has been used to produce TiAl intermetallics and the resultant microstructure and mechanical properties were analysed in detail [21]. The effects of heat treatment have also been evaluated [22]. The first successful application of electron beam melting (EBM) on fabricating TiAl components has been reported to consolidate Ti–47Al–2Cr–2Nb powders. Electron beam melting has been first reported to successfully consolidate titanium aluminide powders [23]. Two EBM processing routes of prealloyed TiAl powders have also been explored to successfully produce near net shape parts [24]. Furthermore, Murr et al. [25] demonstrated the potential to build near net shape and complex titanium aluminide products directly using powder-bed EBM technology for aerospace and automotive applications. Biamino et al. [26] recently succeeded in producing γ-TiAl based alloy with low levels of internal defects and consistent tensile properties by using powder-bed EBM.

Nevertheless, the powder based systems frequently used in the above studies are prone to high impurity levels in the output materials. It has been demonstrated that the wire-feed processes are more economical and less susceptible to contamination from the atmosphere in comparison to processes using powders [27]. Mostly for these reasons, it may be prudent to focus research activities on wire-based processes. However, no information is currently available on the use of material feeding methods other than prealloyed powders to produce titanium aluminide components.

The current investigation concentrates on an innovative additive layer manufacturing approach for titanium aluminides. The gas tungsten arc welding (GTAW) process is combined with separate wire feeding of commercially pure Ti and Al wires to perform in-situ alloying of the two elements. The wire feeding ratios are chosen so that a γ-TiAl alloy is produced. The potential of this new manufacturing method has been proved in our previous studies [28,29]. Processing parameters including arc current, interpass temperature and wire feed rate ratio have been investigated on microstructure and microhardness of γ-TiAl components fabricated by GTAW-ALM. Further, for purpose of producing the components of acceptable quality, repeatability and reproducibility, it is also important to understand the microstructural evolution and the variation of mechanical properties within one build. A few of previous studies have reported the effect of distance from the build plate on the microstructure and microhardness variation within the additive manufactured Ti–6Al–4V part produced by EBM [30], laser-based process [31] and wire and arc based technique [32]. However, no previous literature can be found to specifically study the effect of location on additive manufactured titanium aluminide alloys. Therefore, microstructural features and mechanical properties of the fabricated components as a function of location are the objective of this study, to understand the effectiveness of GTAW-ALM process in producing titanium aluminide components with the desired properties.

2. Experimental procedures

A GTAW current of 120 A and 3.5 mm arc length were applied at a travel speed of 100 mm/min, these parameters being found to be acceptable through several preliminary trials. Commercially pure Ti plates of 6 mm thickness were used as substrates for depositing the alloys. The GTAW torch was focused on the substrate to create a melt pool into which the feed materials were delivered by a twin wire feeder arrangement. The first feed stock was 1.0 mm diameter commercially pure Ti wire at 750 mm/min feeding speed, while the second feed stock was 0.9 mm diameter pure Al wire delivered at 870 mm/min. The deposition process was protected from atmospheric oxidation by using an appropriately designed argon gas shielding device, to produce a final product with minimal oxygen and nitrogen contamination. Fig. 1a and b shows the experimental setup and schematic diagram of the manufacturing process.

The deposited wall components (Fig. 1c and d) typically have a length of 100 mm and a width of 10 mm. Two build heights of 19 mm and 45 mm were used, depending on the specimens

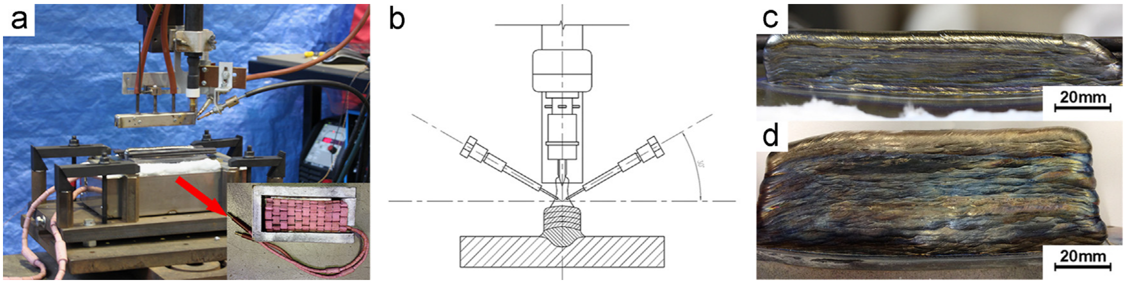

Fig. 1. Experimental setup of the GTAW-ALM process and the typical wall components: (a) experimental setup of the manufacturing process, (b) schematic representation of the process, (c) and (d) examples of titanium aluminide components.