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In-situ synthesis of titanium aluminides by direct metal deposition

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ABSTRACT

This study explores the capabilities of methods for in-situ synthesis of titanium aluminides using the Direct Metal Deposition process. This allows for the functional grading of components which will be required for next generation aerospace components. The feasibility of three techniques are explored here; firstly, a new process of powder preparation for Additive Manufacturing, satelliting, in which a larger parent powder is coated with a smaller powder fraction. Here, Al parent particles are satellited with fine TiO_2 to produce an intermetallic matrix composite with Al_2O_3 particulates. The satelliting procedure is shown to increase capability and mixing of in situ synthesis. Secondly, combined wire and single powder feeding is explored through the use of Ti wire and Al powder to create Ti-50Al (at%). Finally, a combination of wire and loose mixed powders is explored to produce the commercially deployed Ti-48Al-2Cr-2Nb (at%) alloy. The simultaneous wire and powder delivery is designed to overcome issues encountered when processing with single powder or wire feedstocks, whilst allowing for on-the-fly changes in elemental composition required for functional grading. Characterisation of the deposits produced, through OM, SEM, and EDX, reveal the influence of key processing parameters and provides a meaningful basis for comparison between the techniques. Results show that it is possible to produce $\alpha_2 + \gamma$ two-phase microstructures consistent with previous studies which have relied upon more expensive and harder to obtain pre-alloyed feedstocks. This represents a move forward in manufacturability for an emergent process type.

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1. Introduction

Functionally graded components are key for next generation aerospace parts, where the ability to tailor material properties within the volume of a part for specific function provides great advantages over conventionally manufactured components (Mahamood et al., 2012). These functionally graded components cannot be manufactured through casting and other conventional manufacturing techniques traditionally used for aerospace parts. Additive Manufacturing (AM) technologies such as the Direct Metal Deposition (DMD) process allow these capabilities and design freedoms to be incorporated into a component as it is built up layer by layer. By varying input materials and processing parameters during manufacture, DMD has the potential to grade material both compositionally and microstructurally to vary material properties within the volume of a part. This provides advantages for tailoring different sections of a part for specific functions, a capability not possible through subtractive manufacturing methods which produce bulk material properties. The process also allows for functionally graded hard faces to be applied to components currently in service and the opportunity to not only repair parts but improve damaged parts beyond their previous capabilities. Shishkovsky and Smurov (2012) have demonstrated functional grading of Ti base coatings manufactured via DMD, by incorporating TiN or alumina ceramic (Al_2O_3) for increased hardness, wear resistance and high temperature performance.

Titanium aluminides present an exciting material development with the capability for use in high-temperature and pressure environments that place large demands on mechanical and creep properties of a material (Loria, 2000). They offer a unique combination of low density, good oxidation and ignition resistance, and excellent mechanical properties at high temperature (Appel et al., 2000). With a density of $\sim$3.9 $g cm^{-2}$ titanium aluminides are a potential candidate for a lightweight alternative to nickel-based superalloys (density $\sim$9 $g cm^{-2}$) currently used for these applications (Dimiduk, 1999). Titanium aluminides are notoriously difficult to process resulting in very high manufacturing costs, in

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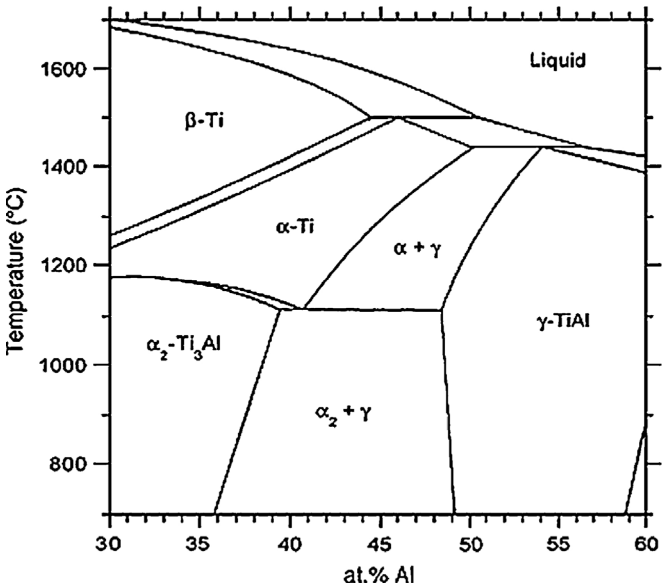

Fig. 1. Modified central portion of the Ti-Al phase diagram taken from Imayev et al. (2007).

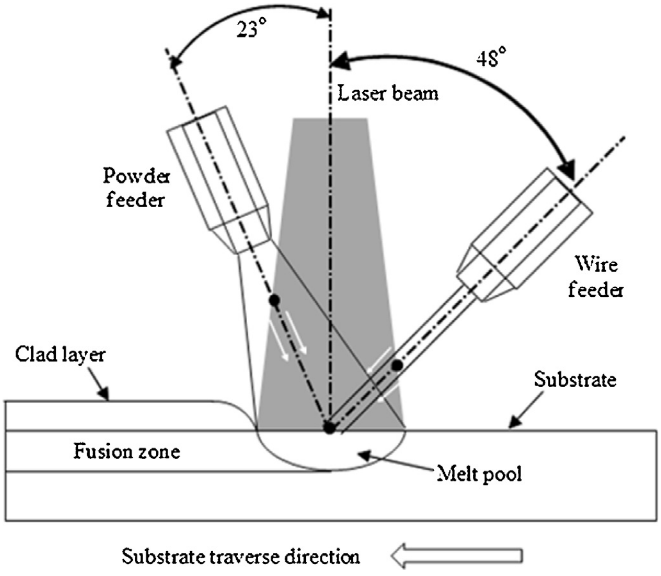

Fig. 2. Schematic of DMD process set up with simultaneous wire and powder feed.

some cases up to 65 times the cost of nickel superalloys (Kothari et al., 2012). Hence there is a need for superior processing routes.

Comprehensive reviews of titanium aluminides are provided by: Loria (2000) reviewed their potential for as structural applications; Appel et al. (2000) reviewed progress in development of titanium aluminides up to the year 2000 related to their mechanical properties and performance; Thomas and Bacos (2011) provided a review on more commercial titanium aluminide alloys and work towards industrial production; and Dimiduk (1999) provided useful comparisons between titanium aluminides and other intermetallic alloys that titanium aluminides have the potential to replace. Dimiduk's comparisons for the mechanical properties required for aerospace applications highlights the potential superior properties of titanium aluminides against other intermetallic alloys. However, Appel et al. (2000) stated that for most of these properties titanium aluminides are currently inferior to nickel-based superalloys, even if the comparisons are made on specific strength alone. This highlights the need for research towards improving these properties and thus enhancing utility. Altering the composition of titanium aluminides has been investigated and micro-additions of elements have been shown to improve properties. Additions of Nb have been shown to increase oxidation and creep resistance and Cr can increase the ductility of titanium aluminides, leading to the development of Ti-48Al-2Cr-2Nb (Kim, 1989), so far the most widely and successfully used titanium aluminide alloy. Many different titanium aluminide alloys have been studied including a wide range of micro-alloying elements all exhibiting different material properties. The advantages of these alloys could be exploited through grading the material within a component from one alloy to another where each would be more appropriate for specific function and service environment (temperatures, pressures, stresses etc.) of particular sections of the component.

The processing of titanium aluminides, presents significant challenge through conventional manufacturing means (Fu et al., 2008). A major challenge is introduced due to the particularly high sensitivity of the mechanical properties to the atomic composition and microstructure of the ordered intermetallic compounds. This is compounded by difficulties in processing without damaging the crystalline structure through mechanical or thermal loading (Lasalmonie, 2006). Ingots produced for forging suffer from coarse grained microstructures with inhomogeneous phase distribution and chemical segregation (Paul et al., 2013). Single (Wang et al., 2000) and often multiple (Liu and Maziasz, 1998) heat treatment procedures are required to achieve final microstructures with acceptable ductility at room temperature whilst retaining high creep strength at elevated temperatures. Titanium aluminides are difficult to machine with their high hardness (up to 454 Hv (Schloffer et al., 2012)) resulting in significant tool wear, poor chip formation, and hence low material removal rates. Therefore net and near-net shape manufacturing processes, such as AM, present themselves as well suited for manufacturing components from this family of materials. Kothari et al. (2012) reviewed the recent advances in processing techniques and a deeper understanding of the material which has been gained, allowing further advancement to be made in this field. This is epitomised in the first commercial uses of titanium aluminide parts used in high performance turbochargers for Formula One and sports cars (Tetsui and Miura, 2002). New processing techniques have facilitated advances towards commercial applications such as with GE and Avio's collaboration with Arcam. This has led to the manufacture of turbine blades with pre-alloyed Ti-48Al-2Cr-2Nb powder using the Electron Beam Melting process, currently used in GE's GENx engines (Thomas and Bacos, 2011). Another powder bed AM process, selective laser melting (SLM), has also been explored for manufacture of TiAl alloys such as beta-solidifying TNM-B1 (Löber et al., 2014) and in-situ TiC particle reinforced TiAl matrix composites. Despite the emergence of titanium aluminide commercial components there is much scope for improving the materials and their manufacture to ensure continued uptake of the material and its establishment as an alternative to nickel superalloys.

This study looks at using the DMD process to produce titanium aluminides through in-situ reactions in order to assess different material preparation methods. Research has been undertaken which explores the use of DMD to produce titanium aluminides but significant shortfalls in the approach have been identified, and the majority of the work to date has related to using pure wire (McElroy et al., 2000) or powder feedstock (Shishkovsky et al., 2012), and in particular pre-alloyed powder feedstocks; Zhang et al. (1998) used pre-alloyed Ti-48Al-2Nb-0.4Ta and Ti-48Al-2Cr-2Nb, and Qu and Wang (2007) pre-alloyed Ti-47Al-2.5V-1Cr, and less investigated methods such as the study by Ma et al. (2014) into in-situ synthesis using elemental Ti and Al wire have been conducted. In this study alternative methods are proposed to improve the manufacturabil-

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