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Machining of Additively Manufactured Parts: Implications for Surface Integrity

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Abstract

Additive manufacturing methods continue to move towards production ready technologies with the widely extolled virtues of rapid transition from design to part and enhanced design freedoms. However, due to fundamental limitations of laser based processes for metal additive manufacturing, there is a significant ongoing need for these parts to be subject to additional machining operations. This paper reports on a study to investigate the machining behavior and surface integrity of Ti-6Al-4V components which have been produced by direct metal deposition using wire feedstocks. Simple geometries are produced and the resulting effect of tooling type is reported. Inhomogeneities in the deposition process as a result of non-uniform cooling and porosity are shown to have a deleterious effect on the surface integrity of the resulting part and the machinability of such components. In addition, strategies for the machining of AM parts which consist of graduated material structures are also proposed here.

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Introduction

Laser deposition is widely used in the manufacture and repair of metallic parts. The process provides a means for components of intricate geometry and desired properties to be manufactured through the use of a laser beam with material being delivered into the laser path on the desired substrate [1]. A number of factors including; alloying control, surface finish requirements and engineering tolerances mean most additive manufacturing techniques are only capable of producing near net shape components. There is often a need for further processing of Additive Manufacturing (AM) parts, therefore finish machining of such components has become imperative to satisfy these requirements. This has led to the development of hybrid systems capable of both building a part and machining the component to a suitable finish within the same work enclosure. This has been used to good effect for new part manufacture and part repair [2,3,4]. Reduction of material wastage is also a key driver in the use of AM, thus the need for post processing through subtractive methods should also be minimised.

Ti-6Al-4V is presently the most widely used titanium alloy and is commonly sought by a majority of metal AM users. Its use accounts for 50% of titanium tonnage in the world [5].The (α)-(β) microstructure of this alloy allows for high strength and formability. Laser cladding of Ti-6Al-4V in wire feedstock and powder form has been successfully undertaken by various authors [6,7,8]. Laser clad Ti-6Al-4V has also been reported to show a grain morphology differing from conventional cast Ti-6Al-4V as a result of the cooling process it undergoes. Solidification and cooling during the laser deposition process is rapid due to the thermal differential between the melt-pool and the previously solidified material/substrate [9]. Thus, for laser deposited Ti-6Al-4V, a Widmanstatten or martensitic structure (columnar growth) has been reported [10], whilst metal-mold cast Ti-6Al-4V form an equiaxed prior grain beta morphology [11].

Titanium and its alloys have been widely regarded as rather difficult to machine materials due to their highly reactive nature, low thermal conductivity, the relatively low modulus

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of elasticity and ability to retain hardness at high temperatures [12]. During machining, titanium alloys tend to weld to the cutting tool –formation of a built up edge (BUE); this consequently leads to tool chipping and consequently, shorter tool life. The low thermal conductivity property also adversely affects tool life as the temperature at the tool-workpiece interface remains elevated due to the heat generated not being transmitted through the workpiece or with the chips generated but rather through the tool. In machining operations such as grinding, even with the use of proper process parameters and conditions, there is a high susceptibility to reduction of fatigue strength due to surface damage [13] such as micro cracks, plastic deformation amongst others.

The purpose of this work is to investigate the changes in microstructure and thus properties after additively manufactured Titanium alloy is machined using two different tool types, since material properties are distinct and variable when compared to conventionally produced feedstocks. Knowledge of this aids in the design of the laser processing stage and also in the decisions on how best to carry out the post processing steps when required.

In the machining of Ti-6Al-4V, as with the properties of other titanium alloys, low cutting speed and high coolant pressure is necessary to achieve superior results due to the properties highlighted above. Other authors have demonstrated the use of various inserts with varying combination of feed and depth of cut with low cutting speeds [14,15] which have informed the parameters and conditions used in this study.

Experimental

In the Direct Metal Deposition (DMD) process used here, a 1.2mm diameter Ti-6Al-4V wire is used as the feedstock material. The wire is fed into a laser beam defocused to produce a beam spot diameter of 3.1mm. A 5mm thick Ti alloy plate was used as the substrate. The set-up was shielded in an Argon enclosure to prevent oxidation of the resulting deposits. These were also allowed to cool under this condition. To adequately mimic an industrial application of the process and with the post process machining process in mind, a circular first layer was built with optimum process parameters obtained from a previous study [8]. Subsequent passes with the relevant step up heights were made on the initial circular base produced. The resulting cylinder has an internal diameter of 70 ±0.5mm and an external diameter of 73 ±0.5mm with wall thickness 2.7±0.5mm and height of 61.7±0.5mm.

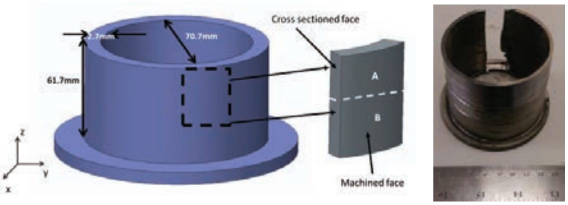

Figure 1: CAD figure and the cylinder after cross- section.

The cylinder was thereafter subjected to outside diameter turning operations. Two different inserts were used in machining two regions of the cylinder. The objective being to determine the effects of using coated and uncoated inserts on the workpiece generated. Both operations were carried out using identical machining parameters (shown in table 1). The coated insert was a PVD TiAlN based coated cemented carbide grade TS2000 with geometry: ISO CNMG120408-MF1. The uncoated insert had the same specifications and tool geometry. In both operations, coolant (HOCUT 795B) was delivered at a rate of 13 litres / min.

The two areas are referred to as ‘’A’’ for the region with the uncoated tool and ‘’B’’ for the region machined with the coated tool.

Table 1: Turning operation parameters.

Cutting Speed	70m / min
Feed Rate	0.15mm/ rev
Depth of Cut	1.25mm

Results

Metallurgical analysis of the clads showed two distinct microstructures within the clads. The structures observed coincided with the clad periphery (zone of re-melting) and within the clad itself. The structures were predominantly Widmanstatten patterns with varying degree of coarseness. The re-melted regions had larger grain size due to the effect of re-melting- this corresponds to a Widmanstatten α morphology. The other regions was however a basket weave Widmanstatten structure without the α segregation.

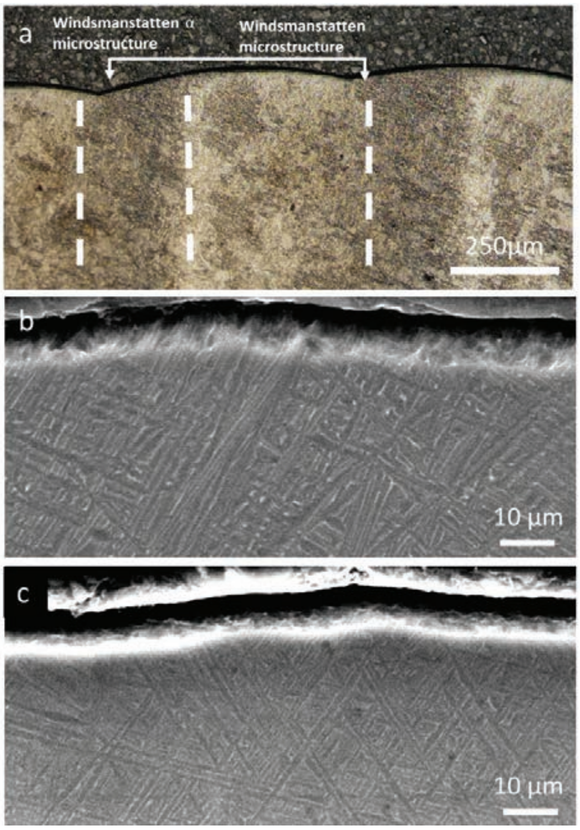

Figure 2:(a) Profile without machining showing variable microstructure,(b) region machined with a coated insert(c) region machined with a uncoated insert.

The regions between clads would be expected to show

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