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Machining of functionally graded Ti6Al4V/ WC produced by directed energy deposition

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ABSTRACT

Additive manufacturing (AM) technologies offer new processing routes for functionally graded materials. At present, parts built using these processes often require additional processing as a result of the characteristic surface finish limitations synonymous with AM processes. A difficulty thus arises in the post processing of these components as volumes within the part have differing material properties by definition and will therefore exhibit variable machinability.

In this study, machining of functionally graded Ti6Al4V/ WC components consisting of a metal matrix composite (MMC) region and a single alloy region produced via direct energy deposition using commercially available tooling is explored. The influence of post processing on surface integrity is investigated and reported. The effect of material variation on cutting forces and tool response along the component is also analysed and reported. Cutting forces within the MMC region are found to increase by as much as 40% which has been subsequently related to the periodic changes in microstructure generated by the layer by layer build strategy. Tool wear mechanisms are investigated and the influence of material pull out on surface integrity of both MMC and single material regions is explored. This study provides an insight into how the layer building strategies, particularly with multiple materials and the resulting variation in microstructure influences the machining of resulting components.

1. Introduction

Additive manufacturing allows for the useof novel material combinations towards improving material strength and prolonging component life. Functionally graded materials have thus far been produced using a variety of processing methods including vapour deposition methods, powder metallurgy and solid free form processes [1]. However, the use of directed energy deposition (DED) techniques in material processing opens up new opportunities for the fabrication of intricate structures and, importantly for functionally graded materials, the controlled use of various material combinations.

Functionally graded components have long found applications in severe operating environments. Wear and corrosion amongst other dilapidating factors are reasons to preferentially vary material properties within component structure. Also, selective addition of high value materials of desirable properties during fabrication to areas prone to damage can reduce the total cost of producing the component as demonstrated by Yamazaki [2]. Functionally graded components are deployed in areas where material combinations offer advantages in properties which are superior to those obtainable from the use of a monolithic material. In the deposition of these components using DED processes, material combinations can either be of the same feedstock (i.e. two powders) or a combination of different types (i.e. wire and powder). Fig. 1 shows an arrangement of DED systems depicting each material delivery method. For these material combinations, by regulating the relative quantities of material delivered to the melt pool and processing conditions, a functionally graded structure can be attained.

As with components produced via powder bed fabrication processes, there is a need for post processing to achieve geometrical tolerances and required surface finish. For these components however, since the primary motive for enhancement of selected regions within the build is often for the improvement of hardness or wear resistance, post processing techniques adopted need to be able to withstand these enhanced properties that inherently pose further significant challenges for

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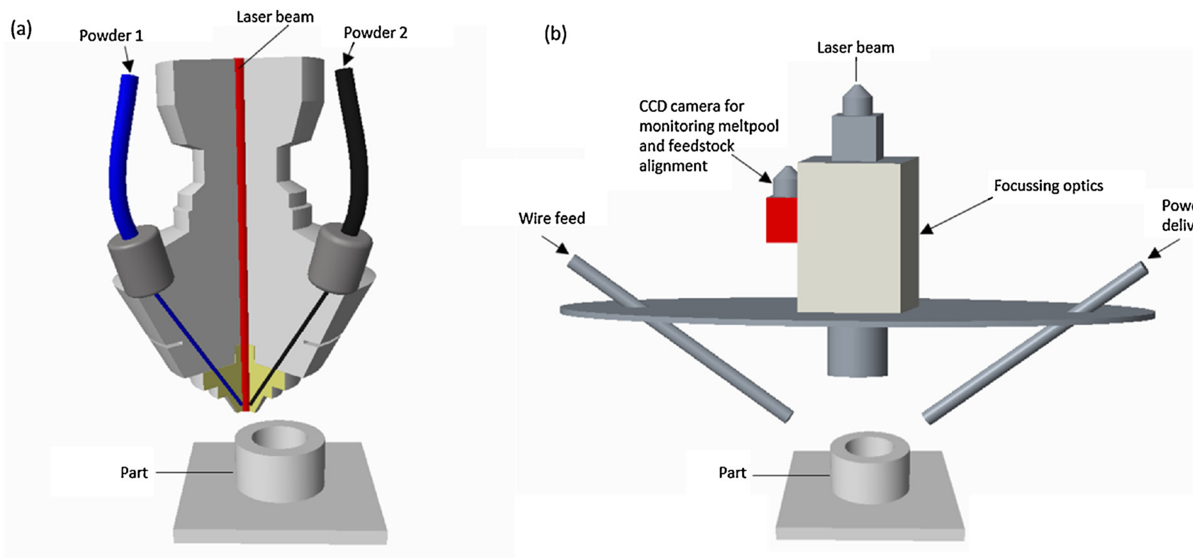

Fig. 1. Schematics showing the two principle methods of material delivery in DED for functionally graded material creation: (a) Coaxial multiple powder delivery (b) Wire and powder side fed delivery.

machining due to their reduced machinability.

In their review on techniques for the fabrication of functionally graded components, Naebe et al. [3] surmised that advances in Additive manufacturing (AM) technologies have opened up new opportunities for the production of components with graded compositions and complex geometries. DED has been demonstrated by various authors to be viable for the production of functionally graded components. In a study on the development of Nickel based surface coatings, Wilson et al. [4], demonstrated the use of a pre blended powder and two powder delivery systems for material delivery to the melt pool. This set up was used in the manufacture of functionally graded components by increasing the composition of the reinforcement material within subsequent layers by reinforcing Inconel 690 with TiC. Liu et al. [5], reported their findings on the fabrication of a functionally graded component using Ti/ TiC powders with two powder feeders in a DED process. The volumetric ratio of TiC to Ti was systematically varied with increasing build height such that at the bottom of the build, α-Ti was reported to be prevalent and at the top, TiC was dominant with a reduced amount of α-Ti. The authors discussed this deposition strategy reduced the number of cracks observed when compared to a single material deposition of TiC on the titanium alloy substrate. The authors also postulated that the gradual variation in composition with build height reduced the interfacial mismatch stresses and the thermal stresses which led to the reduction in number of cracks. Zheng et al. [6], investigated the effects of using TiC coated with Ni as the reinforcement material and Inconel 625 as the matrix material in a laser deposition process. The authors reported that coating TiC powder with Ni caused an increase in strength of the resulting components, as the components became less susceptible to the remelting of the TiC particles during deposition. Improvements in mechanical properties of the Ni coated TiC- MMC when compared to uncoated TiC – MMC was also reported. The authors attributed the improvements in mechanical properties to the TiC - laser beam interaction and improved flowability of the material. In a study to investigate the production and effects of intermetallic phases in a Ti-Al system during laser deposition, Shishkovsky et al. [7] varied the percentage composition of the constituent materials as the build progressed. The authors reported an irregular variation in microhardness along the build direction. This was attributed to localised hardness due to the formation of intermetallics. Formation of cracks at the grain boundaries were reported to be due to these intermetallics. Variations such as these are common place in metal AM processes due to the anisotropic nature of the resulting microstructures. During post process machining, the presence of such intermetallics along the cutting surface is expected to increase machining forces, adversely influencing tool life and surface finish.

Farayibi et al. [8] using a DED process, demonstrated the manufacture of a cylinder with varying material composition of a titanium alloy with tungsten carbide (WC) along the build. In the study, a powder- wire combination was used in achieving the build and the WC composition was varied at different regions of the cylinder. The authors commented on the evolution of energy density during the build process towards achieving a consistent build. By adjusting the process parameters during material deposition, the authors ensured the energy density was kept within a specific threshold. This was used to prevent the development of undesirable intermetallics and to avoid the formation of defects in the build due to excessive thermal input. Abioye et al. [9], investigated a process for fabricating a Ni-Ti structure for medical applications using DED. The authors attempted to improve the biocompatibility of the resulting component by improving the corrosion resistance through the control of the Ni content. The authors also demonstrated the use of machining for improving surface finish and removal of surface cracks on the produced component. The effects of machining on the substructure was however not investigated further and this could have a significant influence on the components mechanical properties. The fabrication of a functionally graded component, consisting of various materials is based on the selective addition within different regions in the component. In this case, the gradation of the component is dependent on the capacity to produce a MMC at the enhanced region.

For DED processes involving MMCs, the amount of reinforcement particles melting within the matrix is an area of interest and opportunity. Although most reinforcement materials have relatively elevated melting points- (SiC- 2730 °C, WC - 2870 °C, TiC- 3150 °C) compared to the matrix materials, typically deposition processes are mostly carried out using energy beams with high intensities, which often leads to full or partial melting of the constituents. Though process parameters can be largely regulated to reduce melting of constituents during manufacture, this characteristic further differentiates components produced using these processes from other processes used in the manufacture of MMC's in terms of attainable microstructures and by extension, mechanical properties.

Machining of MMCs' has been widely reported and the characteristics of the machining processes for particulate MMCs are known. As expected, the presence of reinforcement materials in these components