Introduction

Functionally Graded Material

Functional graded materials (FGMs) are characterized by a variation in composition or structure over a distance, resulting in corresponding changes in material properties. Early FGM developments included thermal barrier materials for aerospace applications, incorporating a gradient in the material’s chemical composition though the coating thickness [1]. There are now considered to be three categories of FGM, namely chemical composition FGM, microstructure FGM, and porosity/geometry FGM. The three categories can be considered as operating on different time scales (Fig 1). This study focuses on the microstructure FGM category and the potential for FGM design and manufacture.

Material Gradient Potential

Linear heat input measures the rate of thermal input in the manufacturing process. Linear heat input, $E_l$, has been defined for a continuous laser as:

$$E_l = P / V$$

where $P$ is the laser power (W), and $V$ is the scanning velocity (mm/s). A review of the literature produced a catalogue of reported L-PBF Ti-6Al-4V material properties for a range of L-PBF linear heat inputs (Fig 4). It is worth noting that a range of mechanical properties were found for the same linear heat input, indicating potential effect of other process parameters including heat treatments etc. However, it can be concluded that linear heat input influences mechanical performance via changes in microstructure in Ti-6Al-4V, thus indicating the potential for Ti-6Al-4V FGM by L-PBF.

Laser Powder Bed Fusion

Powder bed fusion (PBF) is one of the seven categories of additive manufacturing (AM) and is particularly suitable for metal printing. In this process, a thin layer of material is spread onto the platform, a finely focused heat source (e.g. a laser) then melts the powder in a 2D profile defined by the required CAD geometry (Fig 2). Subsequent layers are then added to construct the 3D part.

Due to the finely focused laser format, laser powder bed (LPBF) offers the opportunity to locally vary the thermodynamics (solidification and cooling rates) by changing the laser properties during the build. This variation in process conditions will result in a spatial variation in microstructure (phase, grain size, orientation etc). This concept has been demonstrated recently in Inconel 718 [2] and AISI 316 L stainless steel [3].

Methodology

FGM Design and Manufacture

Two manufacturing strategies were proposed, namely differential equation FGM (manufactured on a Renishaw AM500 at Irish Manufacturing Research Centre, Mullingar, Ireland) and stepwise parameter gradient FGM (manufactured on an EOS M280 at TRT3D, UK). In both cases, linear heat input was maintained constant through the part, but laser power and speed were modified. The stepwise FGM specimen design is shown in Fig 5, and the parameters of both strategies are illustrated in Fig 6.

Experimental verification

As-built samples were then sectioned and polished for experimental and microscopy studies. In order to account for PBF material anisotropy and heterogeneity [6], a sectioning scheme was implemented as shown in Fig 4.

Nanoinindentation was carried out on Keysight Nano Indenter G200 to investigate local variation in hardness and elastic modulus. 10 X-Ray imaging was conducted on a Scanco UCT 100 (NUI Galway) and a Phoenix Nanotom SCT scanner (SEAM, Waterford Institute of Technology) and density measurements were verified via an Archimedes density test. Optical and SEM imaging were conducted on Olympus BX51M and Hitachi S5200D Variable Pressure Scanning Electron Microscope.

Results

A gradient in material defects was evident in the SEM and optical analysis (Fig 8). The Zone 4 - Zone 5 interface (Fig B-c) revealed large pores and cracks with partially melted particles, likely due to the insufficient heat input. Optical image in Fig B-e shows much more porosity at Zone 5 than the other four zones. The pores at Zone 5 are irregular shaped while those at Zone 1 are spherical. A previous study [7] concluded that the irregular pores are caused by lack of fusion, which could be caused by the low laser power (25W) used at Zone 5.

Conclusion and Future Work

This study has demonstrated the manufacturing of solid Ti-6Al-4V FGM material by L-PBF with a 34.11 % and 26.62 % gradient in elastic modulus and hardness, respectively by varying the process parameters during the build.

Two FGM manufacturing strategies were designed for L-PBF additive manufacturing, with the differential equation samples currently undergoing microscopy and nanoinindentation analysis.

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