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Functionally graded properties in directed-energy-deposition titanium parts

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ABSTRACT

The directed energy deposition (DED) process can directly build full-density, high-performance, complex metal parts by melting metal powder with laser scanning. Functionally graded properties are characterized by gradual property variations over the volume according to the designed pattern. This study investigated the functionally graded properties obtained from DED of titanium powder. The formation of titanium nitride in the laser-melted layer has a strong potential to increase the hardness of the titanium alloy. Thus, the hardness of the deposited part was controlled by changing the concentration of nitrogen in the shielding gas. Furthermore, the effect of laser surface remelting on the deposited layer was investigated to control the surface qualities of the part, such as the roughness, hardness, and surface colour. From the analysis, a functionally graded part having variable hardness was obtained on a trial basis, and the proposed method is shown to be feasible with a high degree of reliability.

1. Introduction

The directed energy deposition (DED) process is a kind of prototyping process where a 3D part is built layer by layer by melting metal powder with laser scanning. DED can build full-density, high-performance, complex metal parts from CAD solid model without using any dies or tools. DED offers advantages of single-stage production and geometric flexibility [1]. A laser beam scans each layer to melt powder particles locally and form a melting pool, which is instantaneously solidified as the laser beam moves away. It is critical to optimize parameters that influence the mechanical properties of the part, such as the laser power, scan rate, gas flow rate, powder layer thickness, beam spot size, and hatch distance task. Titanium and its alloys have been used in various industries due to their excellent properties, such as a high strength-to-weight ratio, remarkable bio-compatibility, and exceptionally good corrosion resistance [2–4]. However, titanium has relatively low wear resistance and is limited in applications with erosion or abrasive phenomena. Forming TiN on the surface of titanium alloy is the most common method to improve the wear and corrosion properties [5–8]. DED can selectively melt a desired portion while the laser beam advances to the layer to which the powder is applied, while solid-state nitriding by plasma nitriding and physical vapour deposition (PVD) or chemical vapour deposition (CVD) can be used to generate nitrides on all surfaces [9–13]. The disadvantage of these processes is that they require long processing time and the mechanical properties of the material may change at high processing temperatures. In case of laser gas nitriding, the process is usually much faster than the conventional nitriding. The thickness of the nitride layer can be easily controlled and selective area can be coated with short interaction time [14–18]. The amount of nitrogen that diffuses into the solidified layer of Ti powder is strongly dependent on the laser processing conditions and the environmental nitrogen content. The formation of titanium nitride in the laser-melted layer has a strong potential to increase the hardness of titanium alloy, so the hardness of deposited layers can be controlled by changing the concentrations of nitrogen in the shielding gas. The manufacturing of functionally graded products by DED is one of the promising techniques for meeting various challenges in several industries [19]. As far as can be expected, titanium part with functionally graded hardness can be obtained by controlling concentrations of nitrogen in the shielding gas. DED with nitrogen shielding gas involves feeding nitrogen gas into the melted pool generated by a laser beam, which allows TiN particles to precipitate during solidification. The effect of nitrogen gas on the resulting microstructure and hardness of Ti–6Al–4V alloy have been investigated in previous studies [20–24]. It was reported that the concentration of TiN dendrites was increased with the gas flow

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Table 1
Chemical composition of Ti powder (wt.%).

Element	Ti	C	O	N	H	Fe
wt.%	Bal.	0.08	0.25	0.03	0.015	0.3

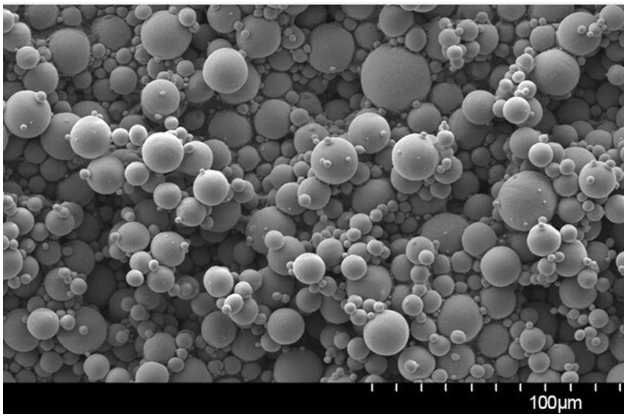

Fig. 1. SEM micrographs of spherical Ti powder with particle size ≤25 µm.

rate and laser energy densities. The fraction of dendrite structures can be controlled by the nitrogen flow rate during the nitriding process. However, laser nitriding at too high nitrogen concentration may cause process-induced cracks in titanium alloys. Crack-free nitrided layers can be obtained by pre-heating the sample or by diluting the nitrogen gas with argon [25–28]. Previous nitriding research primarily focused on controlling the nitrogen flow rate and laser heat input to obtain a crack-free nitrided layer. In the current study, multiple shielding gases having different nitrogen concentrations have been used to produce a functionally graded part without any process-induced cracks. The effect of remelting on the surface properties of the built parts was investigated to further enhance the properties of the deposited layer. From the experimental results, functionally graded Ti-gears were formed by the DED process. A part with functionally graded hardness was fabricated by controlling the mixing ratio of nitrogen and argon gases in the shielding gas. The effect of laser surface remelting on the deposited layer was also investigated to control the surface qualities of the part, such as the roughness, hardness, and colour. A hardness test and microscopic analysis were carried out to characterize the functionally graded properties.

2. Material and methods

Spherical pure Ti powder with particle sizes of about 25 µm or less was used for the DED experiments. The chemical composition of the powder is shown in Table 1, and the morphology is shown in Fig. 1. As Ti-6Al-4V material has better thermal stability than pure Ti and has excellent heat resistance, the DED experiments were performed using a Ti-6Al-4V base plate with a chemical composition of 89.142% Ti, 6.530% Al, 3.890% V, 0.035% Mo, 0.128% Fe, 0.020% Zr, 0.024% Si, 0.050% C, and 0.181% O [29,30]. For cleaning, the base plate was polished with 1200 grit SiC paper and then degreased using ethanol and acetone.

Fig. 2 shows the DED system used in this study. The radiation source is a 200-W fibre laser (IPG YLR-200, IPG Photonics Company, Germany). The wavelength of the laser is 1.07 µm, and the laser beam diameter is 0.08 mm at the focal position. A scanner (hurrySCAN®20, SCANLAB, Germany) was used to control the laser scanning. The vertical movement of the cylinder was driven by a motor.

In the DED process, a shallow layer of Ti powder is applied by a layering bar. The laser beam scans the powder bed according to the slice data of the structure and locally forms a solid area on the base plate. The building cylinder is lowered by one-layer thickness for the next layer of powder and laser melting. The Ti powder-covered samples are processed in an enclosure that is continuously flushed with a shielding gas at atmospheric pressure. The deposited layers obtained by DED were sectioned across the laser-treated layer to measure the depths of layers and the microhardness. Polished specimens were chemically etched using Keller's etchant for one second. After etching, the specimens were cleaned with alcohol and dried using hot air. The microhardness was measured on a transverse section at a distance of 0.1 mm below the layer using a microhardness tester and a load of 150 g. OM (optical microscopy), XRD (X-ray diffraction), and EDS (energy-dispersive

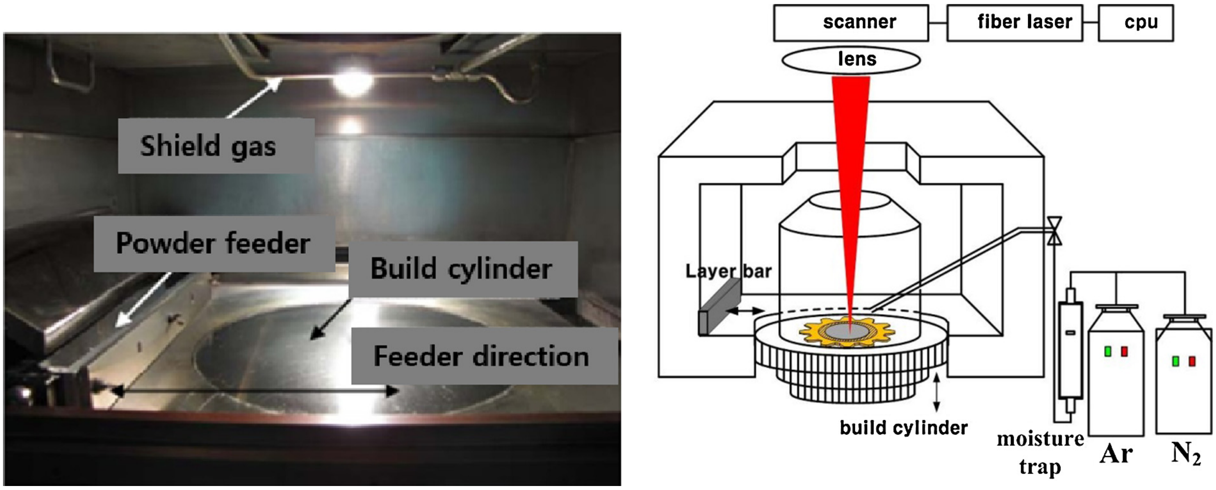

Fig. 2. Schematic of the directed energy deposition system.