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Laser aided direct metal deposition of Inconel 625 superalloy: Microstructural evolution and thermal stability

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ABSTRACT

Direct metal deposition technology is an emerging laser aided manufacturing technology based on a new additive manufacturing principle, which combines laser cladding with rapid prototyping into a solid freeform fabrication process that can be used to manufacture near net shape components from their CAD files. In the present study, direct metal deposition technology was successfully used to fabricate a series of samples of the Ni-based superalloy Inconel 625. A high power CO_2 laser was used to create a molten pool on the Inconel 625 substrate into which an Inconel 625 powder stream was delivered to create a 3D object. The structure and properties of the deposits were investigated using optical and scanning electron microscopy, X-ray diffraction and microhardness test. The microstructure has been found to be columnar dendritic in nature, which grew epitaxially from the substrate. The thermal stability of the dendritic morphology was investigated in the temperature range 800–1200 °C. These studies demonstrate that Inconel 625 is an attractive material for laser deposition as all samples produced in this study are free from relevant defects such as cracks, bonding error and porosity.

1. Introduction

Inconel 625 (Alloy 625) is a nickel-based superalloy strengthened mainly by the solid-solution hardening effect of the refractory metals, niobium and molybdenum, in a nickel–chromium matrix [1]. Alloy 625 was originally developed as a solid-solution strengthened material. It was soon determined that the alloy is somewhat precipitation (age) hardenable [2–5]. Inconel 625 exhibits precipitation hardening mainly due to the precipitation of fine metastable phase γ'' [Ni_3Nb] after annealing over a long period in the temperature range 550–850 °C [3]. Moreover, various forms of carbides (MC, M_6C and $M_{23}C_6$) can also precipitate depending upon the time and temperature of ageing. Alloy 625 has found extensive use in many industries for diverse applications over a wide temperature range from cryogenic conditions to ultra hot environments over 1000 °C [6–9]. The alloy is endowed with good combination of yield strength, creep strength, fatigue strength and excellent oxidation and corrosion resistance in aggressive environments. Moreover, its good weldability and fabricability have made it the choice for many diverse applications. Thus, over 50 years, alloy 625 has been widely used in aerospace, chemical, petrochemical and marine applications. However, many of the Inconel 625 components are highly complex shapes that are very expensive to produce due to extensive machining [10].

Direct metal deposition (DMD) technology [11,12], developed at the University of Michigan, is a laser aided rapid manufacturing technology which can be used to fabricate porous or solid metallic parts directly from CAD model. Manufacturing processes, similar to DMD, have been developed with different names at various laboratories, such as direct light fabrication (DLF) [13,14] at Los Alamos National Laboratories, Laser Engineering Net Shaping (LENS) [15,16] at Sandia National Laboratories, selective laser powder remelting (SLPR) [17] at Fraunhofer Institute (Germany), etc. The basic principles of these technologies are similar that they use a focused laser beam as a heat source to melt metallic powder and create a three-dimensional (3D) object. The key characteristics of these manufacturing processes such as DMD and LENS have a feedback control system that provides a close-loop control to maintain a uniform deposition thickness, thus saving precious post-machining time.

Like rapid prototyping, the DMD process starts with a CAD design. First, the CAD model of the component is sliced into a series of parallel layers with a build height typically 1/4th to 1/3rd of the laser beam diameter. Then, the tool path is generated to fill each layer and subsequently the tool path output data is then post-processed, converting the tool path data into conventional CNC G and M codes. Next, the post-processed data is downloaded into the DMD machine. In the DMD process, a high-energy laser beam is focused onto the substrate or a previously deposited layer to

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form a melt pool; metal powders are simultaneously delivered into the melt pool by a specially designed coaxial nozzle. The nozzle is designed such that the powder streams converge at the same point on the focused laser beam. A CNC system is used to control the nozzle and beam focusing optics as per the tool path generated from the CAD model. Thus, a three-dimensional object is formed layer by layer.

The DMD technology has many potential applications, including production of near net shaped components, surface coatings, part repairing, and fabricating functionally graded materials. However, the production rate of the DMD process is low compared to the conventional manufacturing processes. Hence, DMD process is especially suitable for repairing or fabricating high-value parts with low production volume. As a particular application, DMD is very attractive to the aerospace and biomedical industries for producing complex-shaped metallic components, which is very difficult to produce by conventional manufacturing processes. Due to the very high cooling rate of the laser deposition process, the microstructure of the resulting part is different from equilibrium structure. Recent studies by Gaumann et al. [18,19] using a laser metal forming technique indicated that it is possible to deposit a single crystal Ni-based superalloy clad by epitaxial growth onto a single crystal Ni-based superalloy substrate. However, very little work is reported on laser aided manufacturing of Inconel 625 in the open literature [20]. In this paper, we present the microstructural evolution, thermal stability and mechanical response of laser deposited Inconel 625.

Table 1
Experimental design based on L9 Taguchi matrix.

Run order	Laser power (W)	Scan speed (mm/min)	Powder feed rate (g/min)	Hardness (VHN)
L1	600	300	8	255
L2	600	375	10	257
L3	600	450	12	263
L4	750	300	10	254
L5	750	375	12	260
L6	750	450	8	262
L7	900	300	12	248
L8	900	375	8	254
L9	900	450	10	260

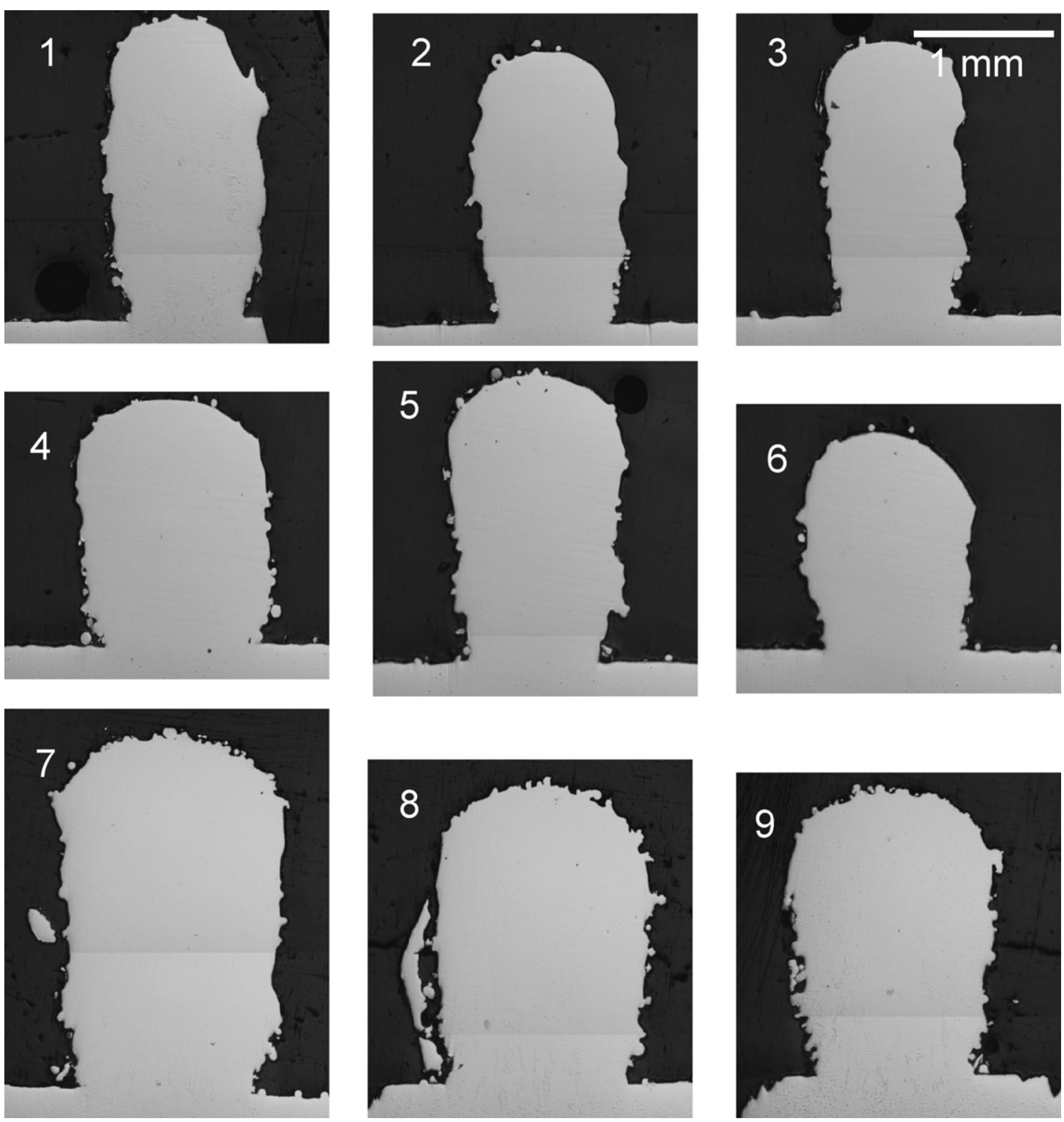

Fig. 1. The transverse-section images of nine as-deposited samples produced with different combination of laser deposition parameters as per L9 Taguchi matrix (Table 1).