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Investigating laser rapid manufacturing for Inconel-625 components

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Abstract

This paper presents an investigation of laser rapid manufacturing (LRM) for Inconel-625 components. LRM is an upcoming rapid manufacturing technology, it is similar to laser cladding at process level with different end applications. In general, laser-cladding technique is used to deposit materials on the substrate either to improve the surface properties or to refurbish the worn out parts, while LRM is capable of near-net shaping the components by layer-by-layer deposition of the material directly from CAD model. In the present study, a high-power continuous wave (CW) CO_2 laser system, integrated with a co-axial powder-feeding system and a three-axis workstation were used. The effect of processing parameters during LRM of Inconel-625 was studied and the optimum set of parameters for the maximum deposition rate was established employing Orthogonal L9 array of Taguchi technique. Results indicated that the powder feed rate and the scan speed contributed about 56% and 26%, respectively to the deposition rate, while the influence of laser power was limited to 10% only. Fabricated components were subjected to non-destructive testing (like—ultrasonic testing, dye-penetrant testing), tensile testing, impact testing, metallographic examinations and micro-hardness measurement. The test results revealed defect-free material deposition with improved mechanical strength without sacrificing the ductility.

Keywords: Laser rapid manufacturing; Co-axial powder-feeding system; Laser cladding

1. Introduction

Laser rapid manufacturing (LRM) is an emerging computer-aided manufacturing technology that uses a laser beam to melt and deposit the injected powder to shape component, directly from CAD model [1]. Manufacturing techniques, similar to LRM, are being developed with different names at various laboratories, such as Laser Engineered Net Shaping (LENS™) at Sandia National Laboratory (USA), Freeform Laser Consolidation at National Research Council (Canada), Selective Laser Powder Remelting (SLPR) at Fraunhofer Institute (Germany), Selective Laser Cladding (SLC) at University of Liverpool (UK), Shape Deposition Manufacturing (SDM) at Stanford University (USA), Direct Metal Laser Sintering (DMLS) at Electrolux Rapid Development (Finland), Direct Metal Deposition at University of Michigan, etc. [2–10]. Distinct from the conventional machining process, all these techniques have the capability to fabricate near-net shape 3-D components and add delicate features onto the existing components with short turn around time, directly from CAD model, in a layer-by-layer fashion by metal deposition using laser. LRM eliminates many steps of manufacturing (e.g. drawing preparation, specific size raw material procurement, man–machine-process planning and intermittent quality checks) and allied human errors. At the manufacturing end, it is an extension of laser-cladding process for 3-D component fabrication by multi-layer overlapped deposition in a pre-determined pattern. In the present study, orthogonal L9 array of Taguchi technique was employed to investigate the effect of laser power, scan speed and powder feed rate and optimize the set of process parameters for the maximum deposition rate. Fabricated components were subjected to non-destructive testing (like—ultrasonic testing, dye-penetrant testing), tensile testing, impact testing, metallographic examinations and micro-hardness measurement. The results are compared with those produced by conventional technique.

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2. Material

Inconel-625 is a non-magnetic, corrosion and oxidation-resistant, nickel-base alloy. Its outstanding strength and toughness in the temperature range cryogenic to 2000 °F (1093 °C) are derived primarily from the solid solution strengthening effects of the refractory metals, niobium and molybdenum, in a nickel–chromium matrix. Nickel and chromium provide resistance to oxidizing environment, while nickel and molybdenum to non-oxidizing environment. Pitting and crevice corrosion are prevented by molybdenum. Niobium stabilizes the alloy against sensitization during welding. Its resistance to chloride stress-corrosion cracking is excellent. It also resists scaling and oxidation at high temperatures. Some typical applications for Inconel-625 are heat shields, furnace hardware, gas turbine engine ducting, combustion liners and spray bars, chemical plant hardware and special seawater applications [11,12]. The chemical composition of the Inconel-625 is listed in Table 1.

3. Taguchi method

The Taguchi method is a proven reliable method of evaluating several design parameters simultaneously with less number of experiments [13]. In the present study, comprehensive experiments were designed as per orthogonal L9 array of Taguchi method to understand the effect of laser power, scan speed and powder feed rate on the deposition rate of Inconel-625. Here, the deposition rate relates to total amount of powder deposited in unit time during the process. Table 2 presents the control factors and their levels used in the experiments. After conducting the experiments as per L9 orthogonal array, the results were converted into signal-to-noise (S/N) ratio data by applying the higher-the-better criterion. The higher-the-better criterion is chosen, as the quality characteristics is deposition rate. This criterion is given by

$$\frac{S}{N} = -10\log_{10}\left[\frac{1}{n}\sum_{i=1}^{n}\frac{1}{y_i}\right],$$

where n represents the total number of tests in an experimental trail ($n = 3$) and y_i represents the deposition rate of the specimen corresponding to the ith test ($i = 1$, 2 or 3). The result of S/N ratio calculations are tabulated in Table 3.

4. Experimental procedure

The LRM setup consists of a high power laser system integrated with the beam delivery system, powder-feeding system and job/beam manipulation system. Fig. 1 presents the schematic arrangement of the LRM machine. In the present experiment, laser beam was generated using a 3.5 kW continuous wave (CW) CO_2 laser system [14] and was transferred to the fabrication point at 3-axis laser workstation [15] using a couple of water-cooled gold-coated plane mirrors and a concave mirror of 600 mm radius of curvature. At fabrication point, a defocused laser beam spot of 2 mm was used for powder deposition. Inconel-625 powder (size range: 45–106 μm) was fed into the molten pool using a volumetric-controlled powder feeder [16] through a co-axial powder-feeding nozzle [17]. Argon gas was used as a shielding and powder carrier gas. The fabrication point was moved as per the required shape with the laser workstation to fabricate the component.

First a number of single tracks were deposited at various parameters to obtain continuous and uniform tracks. This had facilitated to determine the range of

Table 2
Control factors and their levels

Control factor	Levels		
	1	2	3
A. Feed rate (g/min)	4.55	6.03	7.6
B. Scan speed (m/min)	0.3	0.5	0.8
C. Laser power (kW)	1	1.3	1.5

Table 3
Data summary of the experiments

Expt. No.	Feed rate (g/min)	Scan speed (m/min)	Laser power (kW)	Mean deposition rate (g/min)	S/N (db)
1	4.55	0.3	1	1.7772	4.947
2	4.55	0.5	1.3	1.651	4.325
3	4.55	0.8	1.5	1.378	2.619
4	6.03	0.3	1.3	1.793	5.069
5	6.03	0.5	1.5	2.434	7.714
6	6.03	0.8	1	1.706	4.631
7	7.6	0.3	1.5	2.944	9.373
8	7.6	0.5	1	2.342	7.388
9	7.6	0.8	1.3	1.978	5.865

Table 1
Chemical composition of Inconel-625

Elements	C	Ni	Cr	Fe	Si	Mg	S	P	Mo	Ti	Co	Nb + Ta	Al
Percentage	0.1	Bal.	21.3	5	0.5	0.5	0.015	0.015	9.2	0.4	1	3.6	0.4