Optics and Laser Technology 103 (2018) 193–198

Contents lists available at ScienceDirect

Optics and Laser Technology

journal homepage: www.elsevier.com/locate/optlastec

Full length article

Laser-aided Directed Metal Deposition of Ni-based superalloy powder

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ARTICLE INFO

Article history:
Received 1 August 2017
Received in revised form 11 December 2017
Accepted 10 January 2018

Keywords:
Laser Directed Metal Deposition
Superalloy
Repair
Diffusion bonding

ABSTRACT

The subject of repairing Ni-based parts with state-of-the-art technologies is increasingly addressed both for research and industrial purposes, aiming to cost saving mainly in aerospace and automotive. In this frame, laser-aided Directed Metal Deposition (DMD) with injection of powder is investigated in this paper since minimal distortion of the work-piece, reduced heat-affected zones and better surface quality are benefited in comparison with conventional techniques. Actual application to overhaul Ni-based components is aimed, therefore homologous powder is fed by means of a 3-way feeding nozzle over the substrate; a disc laser is used as heat source. The chemical composition of both the substrate and the powder is preliminarily investigated via areal and punctual EDS inspections.

A 2-factor, 2-level experimental plan is drawn to discuss the main effects of the processing variables laser power and processing speed. Namely, the resulting trends are given and compared with similar findings in the literature. Interestingly, dilution as a measure of metal affection is found to be lower than 25%, hence the operating window is deemed to be suitable for both repairing and fabrication of parts. Eventually, repairing by means of side overlapping and multi-level deposition traces on artificial square-shaped grooves is performed: indeed, similar slots are made before DMD to preliminarily remove any local imperfection upon improper casting of the part in the actual industrial process. Although a number of micropores are found, the process is deemed to comply with usual referred standards; in particular, a proper processing window has been found to prevent the occurrence of hot cracking which usually affects the compliance to stress.

1. Introduction

Proper actions are required to the purpose of cost saving, mainly in aerospace and automotive, to keep parts and devices in working order. Indeed, specific damages must be addressed when demanding conditions of temperature, wear and mechanical stresses have been experienced [1]. Also, overhaul of new parts could be required to fix minor local manufacturing imperfection resulting from improper casting.

Since part replacement would result in increased costs for any component of complex geometry, a number of innovative technologies are offered in the literature. Among them, laser-aided Directed Metal Deposition (DMD) in the frame of additive manufacturing is receiving increasing interest and has been developed with different names and similar principles by a number of laboratories and manufacturers, as reported in the literature [2–5]: a laser beam is used as focused heat source to scan the surface, thus creating a melting pool over an existing substrate. Metal impinging the pool is fed concurrently (i.e., in single-stage processing) resulting in metallurgical bonding to the substrate thanks to fusion and diffusion; side overlapping is accomplished to process wider surfaces [6]; multi-layer deposition is required for 3D fabrication. Minimal distortion of the work-piece, reduced heat-affected zones and better surface quality are benefited in comparison with conventional coating and repairing techniques such as arc welding or plasma spraying [7,8]. Even further advantages are achieved in terms of processing speed thanks to new generation high-brightness lasers, with increased beam quality [9]. Enhanced productivity is benefited and grounds are given for automation and reduction of the overall processing time; these features are required in adaptive and flexible manufacturing environments and factories of the future [10].

At present, two possibilities of feedstock are offered: wire and powder, the former being preferred in general for its lower cost and lower probability of oxide content [11], the latter for being flexible in materials and allowing higher precision for local repairing [1] with better surface quality and bonding strength [6,12]. Nevertheless, since a number of processing parameters are involved, a statistical analysis of the responses is usually suggested [13,14]. With this respect, efforts have been made to predict the

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https://doi.org/10.1016/j.optlastec.2018.01.042
0030-3992/© 2018 The Author. Published by Elsevier Ltd.

cross-section of the metal deposition via mathematical models [15,16], based on some level of prior experimental work. Nevertheless, depending on the applications, multi-trace and multi-layer depositions are required to address wide damages, hence a number of further geometrical models and profiles have been discussed to predict the resulting features of overlapping traces [17]. To the specific purpose of repairing of complex parts, a feedback close-loop control has been suggested to maintain uniform thickness of deposition, so to save time for post DMD processing [2].

A wide range of Ni-based components are used in aerospace to benefit from combined mechanical strength, creep rupture properties and resistance to oxidation against demanding stress and temperature [18,19]. Therefore, DMD of superalloys for repairing and overhauling is worth investigating. At first, the subject has been discussed in the literature in the field of laser welding, thus offering a valuable insight to be shifted to additive manufacturing, hence to laser-aided DMD. It has been shown that Laves phases or intermetallics may result from cooling and may ease both the initiation and propagation of microcracks [20]; nevertheless, when properly setting the processing parameters to benefit from lower thermal input (i.e., the ratio of power to speed), the requirements for homologation of welding for aerospace have been matched [21,22] and free of cracking weldability has been proven [23].

Given this background suggesting possible successful results, repair and manufacturing of a wide range of Ni-based superalloys, including CMSX-4, Inconel, NiCrAlY, Rene N4 and Waspaloy, has been investigated by means of laser-aided DMD with metal powder [19]; Ni-coating has been considered even for aluminum powder to improve the process in terms of absorptance, residual porosity and resulting strength [24]. At first, it has been shown that proper care must be taken with respect to virgin Ni-based powder [25]: namely, small particle size and narrow particle size distribution lead to uniform microstructure and high tensile strength; furthermore, residual porosity and crack initiation are affected by laser power. Among other concerns, possible contamination of the parent metal must be restrained, in agreement with general practice on DMD: to this purpose, dilution is usually considered [6,14], to index the result of mixing with the substrate.

In general, a crucial challenge is offered by single crystal superalloys, as deposition lead to formation of stray grains yielding to cracking [26]. Moreover, a further challenge is offered by randomly oriented or curved surfaces which may appear in actual applications of repairing and rapid manufacturing over Ni-based parts, irrespective of their crystalline structure [19].

A face-centred cubic superalloy is considered in this study; strength is enhanced thanks to fine distribution of γ' precipitates $Ni_3(Al,Ti)$ [18]. During solidification and depending on the processing parameters, coarser precipitates result; moreover, Mo and Ti carbides may form along the grain boundaries. As for any Ni-based superalloy, the resulting microstructure of the deposited metal is expected to depend on the direction of processing and the parameters [19]; as a consequence, it may differ from the equilibrium structure due to high cooling rates [2]. A full operational original microstructure must be restored by means of 1190 °C solution heat treating, in vacuum, for one hour [27].

Laser-aided DMD with injection of homologous powder has been investigated in this paper over flat surfaces. The effect of the main processing parameters, power and speed, on the geometry of single-trace depositions has been discussed. A condition of processing, preventing cracking, has been selected to be implemented in multi-trace, multi-layer deposition strategy inside a square-shaped groove, aiming to give grounds for real application of the process in an industrial environment.

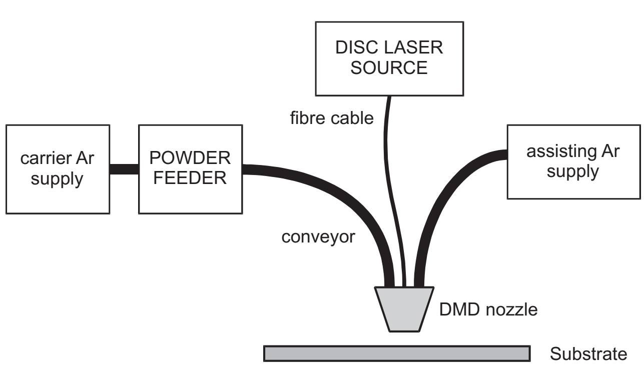

Fig. 1. Laser deposition line, base components.

2. Experimental procedure

2.1. Laser deposition line

To perform DMD for both single- and multi-trace processing, a laser deposition line has been arranged (Fig. 1). A fibre-delivered, Yb:YAG disc laser source, operating in continuous wave emission (Table 1), has been used. The movement of the laser head has been accomplished by means of a 6-axis industrial robot with dedicated controller. An in-built feeding nozzle has been moved with the laser head. A 3-way feeding nozzle, receiving the base metal from a powder feeder with oscillating conveyor, has been used to supply the powder to the deposition line. Thanks to this device, wider and thicker traces are produced with respect to single co- or off-axial feeding, to the purpose of shifting the optimization to real application where throughput instead of precision is crucial; nonetheless, dressing is planned upon DMD to match the nominal dimensions.

Namely, three stream cones of metal powder enclosing the laser beam are provided (Fig. 2); each stream is injected by its separate argon conveying flow. Argon as well, flowing coaxially to the laser beam, has been considered to shield the melting pool from the environment, in agreement with similar applications in the literature [28,29]. A 12 mm stand-off has been allowed between the tip of the feeding nozzle and the reference plane, so that the minimum size of the streams is delivered to the surface of the component. A tilting angle of 4° has been given to the laser head, in agreement with common practice to process metals to prevent back-reflections from entering the optics train.

Since repairing is aimed, homologous powder has been used; gas-atomized Ni-based powder, 50 μm mean particle size, has been used over a substrate of same nominal chemical composition; as a steady feeding rate must be provided consistently, the powder has been preliminarily dried so to flow properly through the conveyor. The chemical composition of both the substrate and the powder has been investigated via Energy Dispersive Spectrometry (EDS) and is given in the relevant section; to this purpose, 15 kV accelerating voltage, 1nA probe current and 3 min probing live time have been set.

An indenting load of 0.200 kg has been used for a dwell period of 10 s to perform Vickers micro-hardness testing.

Table 1
Main technical features of the laser system.

Parameter	Value
Maximum output power [kW]	4.0
Operating nominal wavelength [nm]	1030
Beam parameter product [mm × mrad]	8.0
Core diameter of the delivering fibre [μm]	300
Spot size of the laser beam on the surface [mm]	3
Spot size of the powder stream [mm]	2.5