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Laser direct writing of Co-superalloy lines for micro-fabrication applications

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ABSTRACT

Co-superalloy lines were deposited on stainless steel by a direct laser writing technique: laser micro-cladding by lateral powder injection.

With the aim of producing small strips as thin and narrow as possible, the mean size of the powder used was 8 μm. Using such fine particles makes conventional powder feeders useless, due to the formation of agglomerates unable to be feed. Therefore a new powder feeder, here described, was designed, constructed and tested. A processing parameters map was established, identifying the working window for laser micro-cladding.

The new power feeder and a high brightness, good beam quality fiber laser allowed producing fine lines just 14 μm wide and 7.2 μm thick. Microstructure and mechanical properties, in terms of Hardness and Elastic Modulus, were evaluated confirming that the fine strips maintain the main characteristics of the hardfacing alloy.

Potential applications include micro-part fabrication and repairing such as micro-moulds, and production of 3D parts at sub-millimetre scales.

1. Introduction

Laser direct writing has been the object of study of many research groups throughout the World for the last four decades [1,2]. And is still today an active field of research due to its precision, relative simplicity, and high yielding rate; but also due to the attractive beauty of the idea behind this technique that is “writing with light” [3,4]. Laser direct writing comprises a family of different techniques used to deposit fine lines of a certain precursor material on a given substrate (including laser induced forward transfer (LIFT), Matrix-assisted pulsed-laser evaporation (MAPLE), laser chemical vapour deposition (LCVD), selective laser sintering (SLS), selective laser melting (SLM), or two-photon polimerization) [5,6]. These techniques are certainly quite different but sharing the common fact that the source of energy is a laser beam.

The miniaturization of objects and devices is one of the manufacturing activities that has most evolved in the last 20 years and has been a driven force pushing the development of different laser and non-laser based techniques [7,8]. One example of miniaturization is the micro moulds used for various applications such as microfluidics or microinjection [9]. Fabrication and repairing of such micro moulds requires the deposition of small amount of a certain material (usually hard and wear resistant) on a given surface [10]. Existing thin film techniques such as Chemical Vapour Deposition (CVD), sputtering in its different variants, pulsed laser deposition (PLD), Plasma-Assisted Chemical Vapour Deposition (PACVD) or Laser Chemical Vapour Deposition (LCVD) allow the deposition of thin layers of a certain material, with high quality (in terms of purity and homogeneity). Usually these techniques are carried out inside a high-vacuum reaction chamber. When the material needs to be deposited on a limited small place, some of the techniques require a mask (reducing flexibility), and if the thickness of the layer exceeds the micrometre, normally a long deposition time is required (exceeding the hour) [11,12].

On the other hand, techniques available to produce thick coatings are rather difficult to be adapted to the micrometre range [13]. Laser cladding is one of these so called “thick coating” techniques that has been successfully modified to produce features at micrometre scale [14,15].

Laser cladding is a well know technique in which a high power laser is used as energy source to melt the precursor coating material over the surface of a given substrate. At the same time a superficial thin part of the substrate is also molten in order to achieve a strong metallurgical bond [16]. The coating precursor material can be applied in different ways, being the blowing powder technique the most robust one. Laser cladding allows producing coatings made of single [17] or multiple layers [18]. Application of coatings produced by this technique range

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from increasing wear resistance [19–21], decreasing friction coefficient [22], improving corrosion resistance [23,24], to biocompatibility enhancement [25–27]. Therefore a broad palette of materials has been applied by laser cladding: from superalloys [28,29] to ceramic materials [30].

In order to apply laser cladding at the micrometric scale (micro-cladding) layers should have a thickness in the micrometre range (i.e.: geometrical features $< 100\,\mu m$). First attempts to produce such coatings used pre-placed pastes [14,31,32]. This technique allows producing thin layers (10 μm thickness range) and 100–200 μm wide. The technique comprises three main phases: pre-application of the paste, laser processing, and thermal treatment. The material finally obtained is not a molten strip but sintered powder.

Using the powder injection technique, fully dense materials were deposited by laser micro-cladding [33,34]. Using co-axial laser micro-cladding the group of Prof. Nowotny obtained clad tracks of Al–Si alloys with lateral resolution well below 300 μm [35,36]. Laser micro-cladding using the powder injection technique show its versatility in works such as that of Bo Yao et al. [37] in which 3D elements made of Ti6Al4V at submillimetre range, were produced. More recently the group of Prof. Beyer developed a new laser micro-cladding variety based on a filler wire coaxial to the laser beam [38]. The technique allows producing high quality layers being the limits to achieve very small sizes based on the diameter of commercial wires. Similar results were obtained using an off-axis wire configuration achieving layer widths between 700 and 800 μm [39].

This technique, as well as the powder injection one, allow a more effective use of the precursor material, being up to 100% in the case of the wire based one [39], in contrast to the powder bed techniques that require the use of a great amount of powder not all being reusable [40,41]. Notwithstanding powder bed techniques already showed their potential to produce 3D metal microstructures such as cardiovascular stents [42].

In a previous work, our group was able to produce strips in the micrometre range (width: 50 μm, height: 20 μm) using the laser micro-cladding technique feeding the powder laterally to the laser beam axis [15,43]. The present work is devoted to explore the limits of the technique on the production of small strips as thin and narrow as possible, while keeping the mechanical properties of deposited layer similar to those of the precursor material.

2. Materials and methods

2.1. Materials

In order to assess the achievement of the objectives set in this work, one of the most used powders in laser cladding was selected as precursor material: a hardfacing Co-superalloy [44]. In order to be able to achieve the smallest strip possible, a powder with mean particle size of 8 μm was used as precursor material (powder provided by Sandvik Osprey; UK). Small quantities of this powder, randomly selected, were analysed by scanning electron microscopy (SEM) and X-ray Fluorescence (XRF) in order to evaluate the morphology and chemical composition. SEM micrograph of Fig. 1 shows a clearly spherical morphology of the powder particles used.

The substrates were slabs of stainless steel (AISI 316) of 60 mm × 60 mm × 10 mm (width, length and height). These plates were polished up to achieve a low surface average roughness of $< 0.5\,\mu m$. This allows identifying the geometry of narrow lines to be deposited.

The complete substrate and precursor properties are summarized in Tables 1 and 2.

2.2. Deposition system

As commented previously, the laser cladding by pneumatic powder injection technique was applied to carry out the experiments. In order to allow more flexibility to position the powder with regard to the laser beam, the powder nozzle axis was placed non-coincident with the laser beam axis. This is known as off-axis nozzle geometry. To generate the clad track, a motorized stage moved the substrate with regard to the laser beam and the powder injection nozzle. The angle between the off-axis nozzle and the substrate can be varied by means of a manual micrometre positioning stage. The basic outline of the method is shown in Fig. 2.

All laser micro-cladding experiments were performed with a high brightness monomode SPI Yb:YAG fiber laser delivering a maximum power of 200 W. The wavelength of the laser radiation was 1075 nm. The laser beam was guided by means of a 50 μm core diameter fiber, coupled to the working station via expanding (×10 factor) and collimating optics, and finally focused exactly in the surface of the substrate through a doublet lens (focal length = 80 mm) in order to reduce optical aberration. The laser beam diameter value was (5 ± 0.5) mm at the output of the optical fiber, and before its expansion. Due to the fact that laser beam quality is a crucial parameter to achieve small lines, it was measured in terms of M^2 by means of a Spiricon (LBA-300PC) analyzer. The measurements showed a value of $M^2 < 1.2$, considered acceptable because a beam diameter of $< 10\,\mu m$ on the focal plane was attained.

2.3. Micro-powder feeding system

The tendency of the precursor powder to form aggregates depends on the effect of the particle density (ρ_p) and the fluid viscosity (μ) on the gas-fluidization behavior. Taking into account that the precursor material has a density of $4800\,kg/m^3$ and that Ar was used as carrier gas, the powder shows a SFE (solidlike-to-fluidlike-elutration) behavior from the gas viscosity point of view. With regard to the density of the carrier gas, the powder is classified as Group C of cohesive material in the Geldart diagram (dotted line in Fig. 1). Therefore, the sum of both behaviors results in a highly cohesive precursor powder that can be fluidized under certain circumstances such as centrifugation, by covering the particles with a second material, or by vibration [45–47]. For that reason a new portable, modular, autonomous, and automated feeder for ultrafine powders has been developed, built and tested in order to achieve the normal fluidization of the powder (Fig. 3). This is an extremely difficult task because the interparticle forces are greater than those that the fluid can exert on the particles [48,49]. These interparticle forces (Van der Waals, capillary and electrostatic forces) are attractive and higher than particle weight, causing the formation of aggregates, which are difficult to be dragged by the gas stream. In order to achieve a complete fluidization of the cohesive powder these agglomerates have to be broken [50,51]. This task has been done by providing an additional energy to the particles in the form of waves of ultrasonic frequency [52–54]. This piezoceramic was powered by an amplificator system. Besides, the system can work with triangle, square and sinusoidal signals. In a previous step to desagglomeration, the powder was preheated in order to reduce its moisture level. Moreover, a fine jet of powder was achieved using a micro-injector. The bi-phasic fluid (gas + powder) mass flows used in all experiments were: 10 mg/s for the powder and 1.9 l/min for the Ar gas.

As the objective of the work is achieving lines as fine as possible, the injection of the powder was made from the side of the laser beam where the micro-clad is being formed. This geometry (“over hill”) is less effective than the opposite one [55]. Saving of precursor powder is achieved as the same time due to the extremely low mass flow ratios used, in the mg/s range, which are 3 orders of magnitude smaller than the typical ones used in conventional laser cladding.

The range of the main processing parameters explored during the tests is summarized in Table 3.