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Laser Metal Deposition of Inconel 625 Alloy – Comparison of Powder and Filler Wire Methods

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Abstract. This article presents comparison of laser metal deposition methods. The main methods presented in this work assume use additional materials in a form of metal powder and filler wire. An important differences and problem with deposition of two different additional materials was presented. A comparison of abovementioned metal deposition methods of Inconel 625 alloy was shown. Microstructure analysis performed on manufactured specimens was presented. Differences in deposition mechanism for both methods were shown.

Introduction

Due to rising of material properties requirements, a rapid development of Additive Manufacturing (AM) was seen in a recent years. The high application potential encouraged researchers to study these processes nowadays. One of this new advanced material is nickel based super alloy Inconel 625, with high content of nickel (greater than 50%) and other elements improving its characteristics. The AM process, particularly using laser as a heat source combine unique laser beam properties with potential of building metal elements [1]. The deposition process was perform using methods such as: Laser Engineering Net Shaping (LENS), Direct Laser Deposition (DLD), Laser Metal Deposition (LMD), Selective Laser Sintering (SLS), Laser Powder-Bed Fusion (LPBF) [2,3]. In prototyping of high alloy materials, with high temperature and corrosion resistance, that are used in nuclear, energetic, and aerospace applications very important aspects is to achieve uniform structure, good properties and avoid presence of defects [4]. One of the most important aspects affected on those properties is a fusion mechanism, used during prototyping of each process. Intensity of beam interaction with additional and based material affects on diffusion of alloying elements from substrate to deposited layers or vice versa [5]. When we consider prototyping of small series production use same material for substrate as an additional high alloy material cost can be very high, however using different material for substrate can affect properties of printed element.

Depending on the deposited material's form (powder or filler wire), the density of obtained material are slightly different. Less power delivered to material occur during deposition of metal powders; however, density of the developed material is limited. More problematic is prototyping with a filler wire is considered. Shape of wire affect on laser reflectivity which is especially difficult when CO2 laser is used. In this case bonding of filler wire with the substrate is obtained by using deep material penetration via the keyhole effect [6]. Another important problem is a mixing ratio of alloying elements between the substrate and the deposited material. Nevertheless, density of printed metal elements using this process are higher, and potential application of this process can't be omitted [7]. Another difference between those two methods is surface condition, after laser metal powder deposition surface smoothness in better, however roughness is lower only in one direction – parallel to deposition direction.

The properties of the deposited material are related to the thermal cycles and chemical composition of the used materials. In this article two main methods of LMD were presented, the deposition of additional material in the form of filler wire and metal powders. In both presented processes additional material is deposited directly on the substrate. Mixing of the alloying elements between substrate and deposited material for analyzed methods is different; therefore, metallographic analysis was performed. Micro and macrostructure study was carried out using Scanning Electron Microscopy (SEM) and elements diffusion was tested with Energy Dispersive Spectroscopy (EDS) analysis. A visual microscopic test was carried out in order to detect potential defects in printed materials. The metallographic structure of characteristic areas was tested, including precipitations [8,9].

The issue discussed in the article holds significant technological and practical importance. The applied method can have a significant impact on improving the quality and durability of machinery in the metal industry [10,11], automotive parts manufacturing [12,13], quality management in the automotive industry [14,15], as well as in the wood industry [16], where machine wear and tear significantly affect worker safety [17,18]. The results obtained during the work can be useful in similar processes utilizing laser processing techniques [19,20], including those in particularly demanding high-quality surgical implants [21-23] and surfaces prone to the deposition of contaminants [24,25]. The LMD technique is clearly competitive compared to the powder-based technique [26,27], although the desired characteristics of the obtained surface layer remain an open question [28,29], especially for specific material coatings [30,31] or alloy substrates [32,33]. An undeniable outcome will be a significant reduction in machine part wear [34-36] and the provision of new material possibilities for research on more efficient batteries [37,38].

Experimental Procedure

The experimental procedure was divided into two separate steps. For every part, Trumpf CO2 laser integrated with TruLaserCell 1005 machine was used. The first experiment concerned deposition of Inconel 625 alloy in the form of filler wire on the S355J2 substrate. The second experiment shows powder deposition of Inconel 625 alloy on the same substrate material. In order to reduce the plasma ionization effect, as a shielding gas helium (5.0) with a flow rate equal to 20 l/min was used. For metal powder deposition additional argon (5.0) was used as a powder conveying gas.

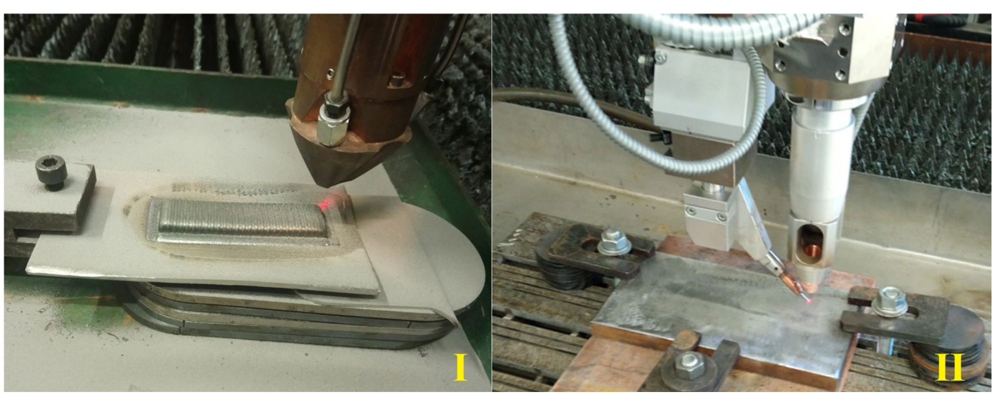

Fig. 1. *LMD prototyping using additional material in form of: I - metal powder, II - filler wire.*

Prototyping processes were performed using two process heads: I - a welding head (focal length equal to 270 mm), with side wire feeder and II – a cladding head (focal length equal to 250 mm) with coaxial metal powder delivery system GTV M-PF 2/2. Deposition of metal powder on the substrate surface was performed with output power equal to 2.3 kW, speed of process head moving equal to 0.8 m/min, and single layer interval – 2.5 mm. The powder feed rate approximately 15 g/min (Fig.1). For the filler wire deposition, output power was set as 3 kW, with process speed equal to 1.5 m/min (Fig.1). Speed of wire feed rate was similar, while wire was oriented at an angle of 45 degrees [39].

Results and Discussion

The obtained specimens have similar dimensions; however, the structures of bead geometries for the both mentioned methods are significantly different. Global observation showed higher substrate material distortion in sample prototyped with filler wire. Moreover, the fusion mechanisms in the deposition process are different for these methods [40]. The microstructure of the obtained specimens showed significant differences; therefore, further metallographic study is presented (Fig.2).

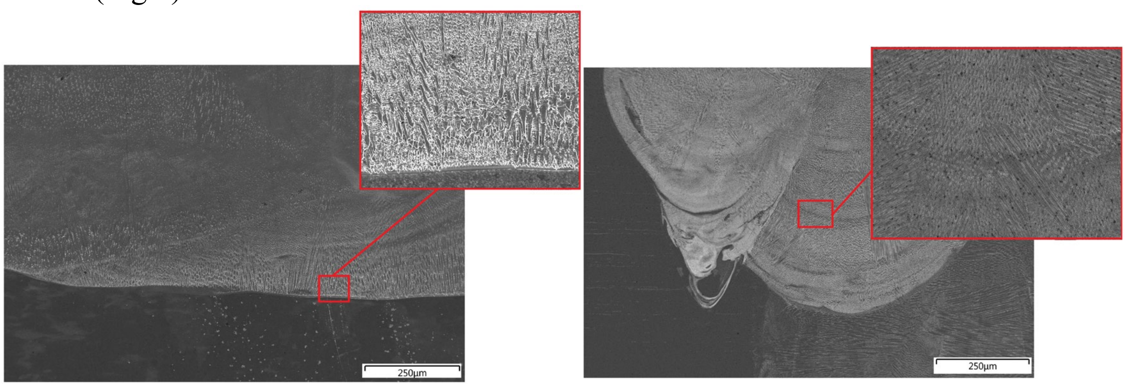

Fig. 2. *Microstructure of manufactured specimens with metal powders (left), filler wire (right)*

The investigated fusion mechanisms are different; in wire deposition there are keyhole effect and high-power density process with depth substrate material penetration, meanwhile in powder deposition the mechanism is based on conductivity phenomenon of melting a thin layer of substrate with molten powder. According to global observation, certain separate regions for all the mentioned methods can be identified. Microstructure in the material manufactured using the wire deposition method is complex, changing according to specimen height; differences in dendritic growth can be observed in all methods [41]. However, in the powder deposition material structure are more uniform, with differences visible only in dendritic growth direction. For both analyzed methods, the upper layers reveal differences only in dendritic growth direction related to each padding bead and dendrite size [42].

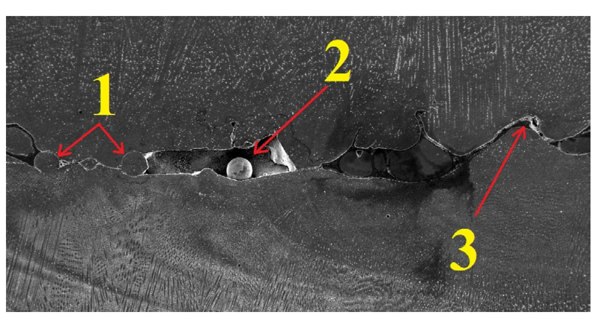

Fig. 3. *Discontinuities in material manufactured using the powder deposition method.*

During metallographic analysis mentioned in introduction section, discontinuities was revealed (Fig.3), where (1) partial molten powder (2), not molten powder particles and (3) gap between printed materials were identified. This type of defects occurs between layers when some sort of disruption appear during melting of metal powder, usually when cooling rate is too high or laser power too low.

Structure of sample prototyped using laser beam and filler wire have complex microstructure (Fig.4), due to occur of keyhole effect the severe fluctuations in the flow field of molten material appears. Structure with typical pillar dendritic (D) alongside with cellular dendritic structure (C) was identified.

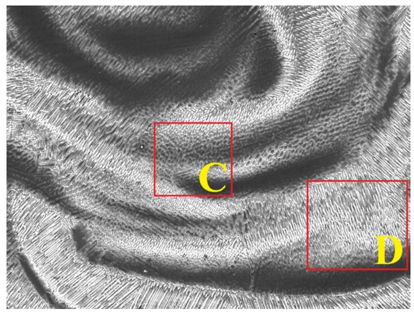

Fig. 4. *Complex microstructure of filler wire deposition specimen.*

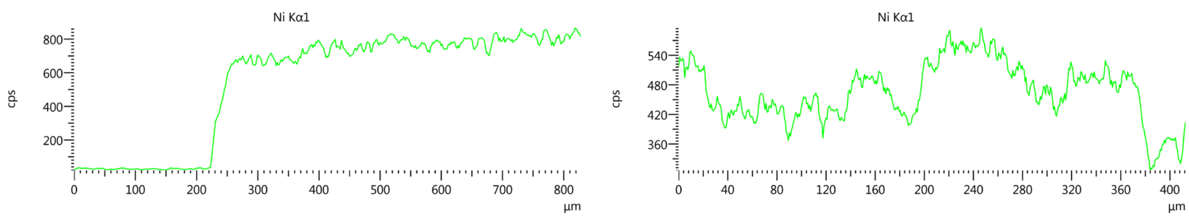

Fig. 5. *Nickel distribution in substrate to deposited material section for: metal powders deposition (left) filler wire deposition (right).*

The materials used for deposition have important differences in chemical composition and structure compared to the substrate material. The aforementioned differences affect diffusion and solidification processes. Deposition parameters were developed according to a separate preliminary study. Global observation showed significant differences in the fusion zone between the substrate and the deposited materials depending on the deposition process. Moreover, macroscopic analysis showed a potentially non-uniform structure in the fusion zones for the wire deposition method and cavity with partially molten powder for the powder deposition method [43]. Microstructure of the manufactured materials is dendritic; however, dendritic orientation differs depending on the deposition method. In the top part of the layers typical fine dendritic structure with secondary dendrites are observed. The cooling rate of the molten pool, and consequently the solidification velocity is higher at the bottom part of the layer and relatively slower at the top part. Non uniform distribution of nickel in Inconel 625 (Fig.5) deposited layers can reduce its properties, especially high temperature resistance and corrosion resistance. The wire deposition alone method via keyhole deep penetration affects intensive mixing of deposited material with the substrate, when the keyhole penetrates the bottom workpiece.

Summary

Analyzed deposition methods are related to direct laser deposition, where filler wire and metal powder were used as an additional material. Deposition of high alloy material is associated with a complex structure formation and numerous inclusions related to the solidification process. In the wire deposition method, a greater thermal gradient appears alongside with more rapid phenomena. Homogenous structure of manufactured materials using metal powder deposition method was confirmed, however, some deposition defects in the form of gas pore and cavity can be observed.

The presented results show significant differences in bonding mechanism between the substrate and deposited materials for both methods. Advantages and limitation of aforementioned methods was presented, where developing metal parts using LMD methods those aspects should be considered in order to avoid part failure or poor properties of prototyped elements.

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