SUSTAINABLE PROCESSING BY ADDITIVE MANUFACTURING

[1] MAZUR, Viviane Teleginski, Industrial Maintenance Technology, Federal Technological University of Paraná, Brazil.
vivianemazur@utfpr.edu.br
[2] d'OLIVEIRA, Ana Sofia C. M., Mechanical Engineering, Federal University of Paraná, Brazil.
sofmat@ufpr.br
[3] MAZUR, Maurício M., Materials Engineering, State University of Ponta Grossa, Brazil.
mzmauricio@hotmail.com

INTRODUCTION

Additive technologies have become an important manufacturing process due to their sustainability characteristics: more efficient use of materials, lowers carbon emission along the production chain, and competitive advantages in the manufacture of additive components. Furthermore, when compared to direct metal deposition technologies such as electron beam or laser, the Plasma Transferred Arc Additive Manufacturing (PTA-AM) emerges as an important additive technique to the fabrication of thicker layers, leading to productivity increases in larger components [1-3]. Other advantages of PTA-AM in relation to direct deposition techniques that use high energy densities include the low cost of equipment and the higher efficiency in the use of materials [4].

The use of metallic powders allows the deposition of harder materials with lower weldability and the customization of the chemical composition for processing, offering a wide range of mechanical properties to the components [5-8]. In this work, the PTA-AM technology was used to process the nickel superalloy Inconel 625, with gradual additions of nickel and aluminum powders, obtaining chemical composition and mechanical properties gradients due to an increasing content of nickel aluminides processed by in situ synthesis. The main goal of this study is to investigate the service lifetime increase of high temperature alloys with feasible technologies for manufacturing or repairing components.

MATERIALS AND METHODS

Plasma Transferred Arc Additive Manufacturing (PTA-AM) was employed to deposit superimposed layers using powder materials as feedstock, with each layer using a different mixture of powders. The substrate material was a MONEL 400 alloy, with nominal composition of 70% Ni and 30% Cu. The initial layer comprises Inconel 625 (IN 625) powder alloy. This is a nickel superalloy, with composition shown in Table 1.

Table 1. Inconel 625 chemical composition, in wt.%, measured by X-Ray fluorescence.

Ni	Cr	Mo	Nb	S	Fe	Al
Balance	20,6	10,3	3,8	3	1,1	0,8

The second composition contains 90% of IN 625 mixed with 10% of a mixture of elemental nickel and aluminum powders in a fixed proportion of 75% Ni and 25% Al, hereafter called Ni-Al (75-25). The third composition contains 80% IN 625 with 20% of the aforementioned nickel-aluminum powder mixture. According to Almeida et al. [7], this proportion allows the in situ reaction between nickel and aluminum, generating Ni_3Al

intermetallics. Due to the Ni_3Al high hardness and oxidation resistance, its incorporation to the IN 625 alloy could lead to further improvements in hardness, wear rate, and also oxidation resistance.

Fig 1. PTA-AM photograph showing (a) the plasma torch in transverse direction and (b) the deposition sequence for second and third layers in longitudinal direction. (c) Schematic drawing of the wear test.

The PTA-AM deposition was performed with a scanning speed of 100 mm/min at 150 A and a powder feeding rate of 7.3 g/min. Argon was used as plasma gas (2 L/min), shielding gas (15 L/min) and powder transport gas (0.8 L/min). The distance between the plasma torch and the surface was fixed at 12 mm. Fig. 1(a) shows a photograph of the PTA-AM in front of the advancing torch, where the feedstock powder can be seen being fed into the plasma torch. Fig 1(b) shows how the layers were superimposed along the deposition direction.

Sample preparation for optical microscopy consisted in cutting small pieces with a metallographic saw, grinding with SiC sandpaper (600, 1200#), polishing with alumina (1, 0.3 and 0.05 µm) on a cloth, and chemical etching with Marble's reagent (4 g $CuSO_4$ + 20 ml HCl + 10 ml H_2O).

The wear rate wd [mm^3/N/m] was assessed by ball-on-disc wear test, and a schematic representation of this is shown in Fig 1(c). The sample surface was sanded with 600# SiC sand and cleaned in an ultrasound bath for 1 minute before wear tests. A 3 mm diameter Al_2O_3 spherical body grinded the sample surface while rotating in a 1 mm diameter circle, corresponding to a length l of 3,14 mm. The test was performed at room temperature, with a load F_n of 5 N, at 450 RPM, completing 40,000 laps (~250 m). After the test, the wear track on the sample surface was analyzed by confocal microscopy, to determine the volume loss V [mm^3]. The wear rate is calculated according to Equation 1:

$$w_d = \frac{V}{F_n \cdot l} \qquad \text{Eq. 1}$$

Images of the wear tracks were acquired using confocal microscopy after the tests, to analyze the volume removed from the samples and their different chemical compositions.

RESULTS AND DISCUSSION

A multilayer gradient was processed using the three materials described previously. The optical micrographs of Fig. 2(a) show the first layer, consisting of pure IN 625 deposited by PTA-AM. Pores are formed near the substrate material, probably due to the mismatch of chemical composition between the substrate and the deposited layers. Refining the post-machining and processing parameters can reduce pore formation. The microstructure consisted of dendrites, growing from the substrate towards the surface. Near the surface, equiaxed grains formed, as expected in a welding solidification process.

Fig. 2. PTA-AM micrographs showing the buildup layers and their compositions: (a) first layer with 100% IN 625; (b) second layer with 90% In 625 and 10% Ni-Al; and (c) third layer with 80% IN 625 and 20% Ni-Al.

Fig. 2(b) shows the second layer superimposing on the first layer. Despite the change in composition with the addition of Ni-Al (75-25) in the deposited powder mixture, no apparent interface was observed in the optical microscopy evaluation due to the partial melting of the previous layer, indicating a continuous microstructure formation. Fig. 2(c) shows the superimposed layers processed with the different compositions, with no apparent defects at the layers interface. This result shows that the modification in the powder chemical composition is feasible to produce additive manufactured layers, without compromising the IN 625 weldability.

The layer dimensions are shown in Table 1, where the penetration depth in the substrate material and the additive layer height were measured. The thickness increase after deposition of the first layer was 1.7 mm. Superimposing a second layer led to a thickness of 3.0 mm, an increment of 1.3 mm. The addition of a third layer resulted in a total thickness of 4.0 mm, ensuring an increase of 1 mm to the additive material. It can be inferred that the deposition of additive layers has a systematic increase in the layer thickness. In PTA processing, it is possible to increase the layer thickness by increasing the powder feed rate, which could lead to productivity increases.

Table 2. Deposited layers dimensions and wear rate.

Layer	Penetration depth [µm]	Additive layer high [µm]	Wear rate [$mm^3/N/m$]
1st Layer	947 ± 15	1735 ± 6	7.5×10^{-4}
2nd Layer	999 ± 23	3041 ± 4	1.0×10^{-4}
3rd Layer	946 ± 12	4056 ± 2	0.9×10^{-4}

The wear tracks for each layer are shown in Fig. 3. It can be observed that as the Ni-Al (75-25) content increased, the track width was reduced. The cross-sectional area of the wear track was analyzed and the wear rate calculated, as shown in Table 1. It is observed that the additions of Ni-Al gradually reduced the wear rate. This indicates that in situ synthesis nickel-aluminide particles occurred and incorporated into the IN 625 alloy, increasing wear resistance.

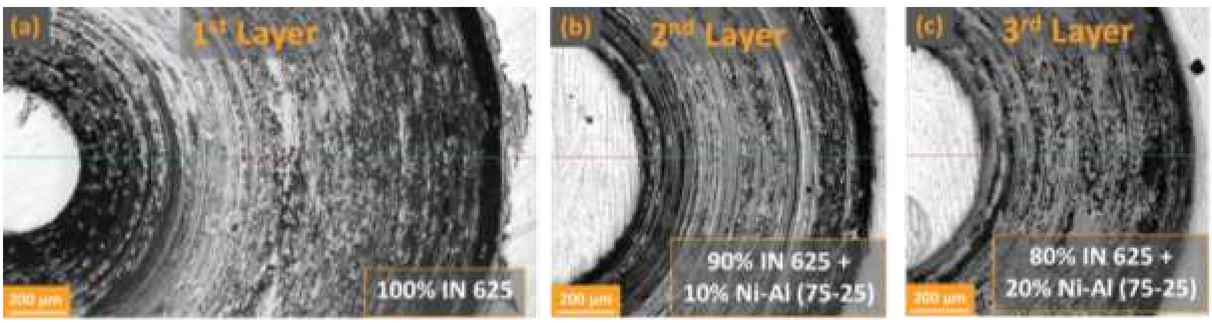

Fig 3. Comparative micrograph of wear tracks for first, second and third layers, revealing the increase on wear resistance as the Ni-Al (75-25) content increased.

CONCLUSION

PTA is a high-efficiency process, adequate to manufacture or repair functionally graded materials, that can be developed to increase service lifetime for high temperature applications. The processed additive layers presented chemical composition and mechanical performance gradients, the latter measured by wear resistance. The amount of Ni-Al (75-25) mixed with the Inconel 625 alloy has a direct impact on the increase in wear resistance, a consequence of the in situ synthesis of hard intermetallic phases. It is important to highlight that the enrichment with hard intermetallics was gained during the one step PTA-AM processing of each layer, indicating high process efficiency and offering sustainability gains.

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