

METAL MATRIX COMPOSITE COATINGS (Ni-ALLOY:NbC) BY LASER CLADDING ON GGG40 SUBSTRATE: QUALIFICATION STEP THROUGHOUT SINGLE-BEADS

Lubar Eduardo Hortmann Santos Rivero

Federal University of Paraná
lubarsantos@yahoo.com.br

Jeferson Trevizan Pacheco

SENAI Institute of Innovation
jeferson.pacheco@sc.senai.br

Moises Felipe Teixeira

SENAI Institute of Innovation
moisesft6@gmail.com

Adriano Scheid

Federal University of Paraná
scheidadriano@gmail.com

Abstract. It is well-known that coatings have been considered in many industrial sectors, for instance, aerospace, marine, and automotive, as a way to improve the components' performance. Among a large variety of coatings processing techniques, laser cladding has shown noticeable technological advances in recent decades. Facing the opportunity to have powder-fed systems, a machine equipped with two independent powder delivery units opens a path for research of functional multi-materials, i.e., either combining different alloys by mixing them during the process or even mixing an alloy and hard particles of reinforcement to form a metal matrix composite coating with the desired microstructure and properties. The latter shows particular interest in component design to improve wear and corrosion resistance or even repair a worn-down surface. The approach is promising and aligned with the best practices of sustainability, since a considerable part of the world's total energy consumption is due to tribological contacts, overcoming friction, and remanufacturing worn parts and spare equipment due to wear-related failures. This work aims to assess the effect of laser power and NbC reinforcement feeding rate on the single-bead composite coatings features by laser cladding process. As the step of cladding qualification, the present investigation is a key point to further development of mechanical parts protected with multi-layered coating areas. Thus, composite coatings were processed with 1.5-, and 3.0-kW and feeding rates of 25, and 50-wt% of NbC to the Hastelloy C276 alloy on GGG40 ductile iron substrate. Characterizations involving bead geometry, defects, dilution, microstructure, and hardness were performed. Results showed larger bead width and lower wettability angle for 3.0 kW. The former is associated with the higher burn-in-shape, as expected for gaussian energy distribution laser beams, and the latter is mainly due to the higher heat input. Dilution from 4 to 11% and 37 to 41% was measured for 1.5 and 3.0 kW, respectively. The microstructure is comprised of Ni-FCC dendrites and interdendritic carbides for non-reinforced C276 alloy. Otherwise, composite coatings showed a more complex microstructure, comprising unmelted particles of NbC, primary petaloid NbC, Ni-FCC dendrites, and interdendritic secondary carbides. Hastelloy C276 showed hardness from 309 to 350 HV₂ whilst it ranged from 418 to 549 HV₂ for composite coatings. Regardless of the laser power, the increase in the NbC feeding rate induced harder composite coatings as a consequence of the higher carbide volume fraction.

Keywords: Laser Cladding; Powder-Fed Systems; Composite Coatings; Hastelloy C276; NbC Reinforcement; Dilution; Microstructure; Hardness; Cladding Qualification.

1. INTRODUCTION

A great variety of alloys and superalloys have been studied to protect the surface of mechanical components and structures to withstand the wear of materials along with service life, to mitigate also the degradation in several corrosive environments, and sometimes to reduce the high-temperature oxidation (Venkatesh, Sriker and Prabhakar, 2015). Beyond the welding process control to preserve the chemical composition of a hard-facing alloy and ensure high wear performance, corrosion resistance frequently appears as the focus of engineers in the selection of coating materials and, facing the context, nickel-base alloys are commonly considered (Mankins and Lamb, 1990; Ferreira, Graf, and Scheid, 2015; Fernandes, Cavaleiro and Loureiro, 2012; Abioye, McCartney and Clare, 2015; Rivero, 2019; Rivero *et al.*, 2020).

Hastelloy C276™ is an alloy designed with a high molybdenum content, which accounts for an attractive resistance to pitting. Also, tungsten and molybdenum act as solid solution hardeners enhancing the mechanical strength of the alloy (Mankins and Lamb, 1990). Previous works (Ferreira, Graf, and Scheid, 2015; Rivero, 2019; Rivero, *et al.* 2020) studied the effect of heat input and the kind of substrate on the microstructure and properties of C276 coatings deposited by plasma transferred arc (PTA) and by laser cladding. Their studies pointed out the rule of heat input control when the chemical composition of the original alloy is the objective. Nevertheless, in some cases, controlled and known dilution may be an opportunity to enhance the hardness and wear performance. The above-referred works have shown that the strong carbide formers in the alloy (W and Mo) combined with selected heat input and substrate may deliver unique sliding wear resistance.

A chance to reach a significant increase in the hardness and wear properties of coatings has been explored not only in Ni-base but in Co-based alloys through alloy carbide managing, usually selecting a high-carbon content low-cost cast iron substrate (Ferreira, Graf, and Scheid, 2015; Rivero, 2019; Rivero, *et al.* 2020, Graf *et al.*, 2019). Research has been carried out by way of a single-bead approach, showing this is a critical step in coatings qualification. The processing begins with the analysis of the single-bead cross-section profile and its geometry to define the further overlapping ratio of multi-bead coatings. Beyond that, the synthesis of a composite coating exploring a laser cladding machine containing a dual powder-feeding system was already reported elsewhere (Pizzatto, *et al.*, 2021). Thus, not only the effect of heat-input on the dilution with different substrates but on the powder melting and incorporation into the melt pool encompasses a field that needs investigation.

At this rate, there is no doubt that Laser cladding by powder injection with a dual-feeding system has been drawing the researcher's attention because of its singular characteristics in processing metallic and composite coatings, as well as high-value component repair and low-volume manufacturing. In the composite coatings synthesis, the laser source concomitantly melts the component surface, the coating alloy, and reinforcement particles powder to form a repaired area or a protective layer (Toyserkani, Khajepour, Corbin, 2005; Zhong and Liu, 2010; Haldar and Saha, 2018; Pizzatto, *et al.* 2021). Additional challenge comes from the microstructural features of laser cladding materials, in turn, are noticeably different from those processed by conventional welding processes because of the higher cooling rates during solidification (Toyserkani, Khajepour, Corbin, 2005; Zhong and Liu, 2010). This work assessed the single-bead geometry, defects, dilution, microstructure, and hardness of Hastelloy C276:NbC composite coatings deposited by laser cladding on GGG40 ductile iron substrate at distinct heat inputs.

2. MATERIALS AND METHODS

Gas-atomized powder-feeding alloy (Hastelloy C276™) with particle sizes from 53 to 150 μm and Niobium carbide reinforcement powder with particle sizes between 10 and 60 μm were adopted in the present investigation. In situ mixing was done from a dual-feeding system in a high-power diode laser (HPDL) PRECO™ SL8600 deposition center with a coaxial torch device on GGG40 ferritic ductile iron plates 12.00 mm thick. Substrate chemical composition and surface preparation procedures followed (Rivero *et al.*, 2020). The chemical composition of feeding materials and processing setup is detailed by (Pizzatto *et al.*, 2021). The single beads were prepared from 1.5- and 3.0-kW laser powers and 25 and 50-wt% NbC reinforcement feeding rates.

Macro and microstructural characterization were done in the beginning, center, and end of multi-bead length after discarding 15 mm from the extremities. The reinforcement thickness or clad height, wettability angle, and bead width were measured from the macrographic analysis. Dilution of single-bead coatings was assessed by the area's method, following the previous works (Ferreira, Graf, and Scheid, 2015; Rivero, 2019). Facing the presence of porosity in some specimens, the area fraction had to be adjusted, subtracting the porous area.

Microstructure analysis was performed in an optical microscope after electrolytic etching in a water solution of saturated oxalic acid, at 3V for 10 seconds. The Vickers hardness under a 2 kgf load was measured on the polished transversal cross-section of coatings.

3. RESULTS AND DISCUSSIONS

Table 1 and Fig. 1 show the single-bead geometry, with larger bead width and lower wettability angle for 3.0 kW. The former is associated with the higher burn-in-shape, as expected for gaussian energy distribution laser beams, and the latter is mainly due to the higher heat input. A most significant degree of porosity was observed for composite coatings deposited with 1.5 kW laser power. Otherwise, the higher heat-input (3.0 kW) induced also a higher substrate melting, in turn, showing some porosity even for non-reinforced specimens (see Fig. 1d). From the previous works (Pizzatto, *et al.* 2021), the porosity is associated with a reaction between the NbC powder which, in turn, contains niobium oxide and probably contributed with the formation of CO and CO₂, i.e, gas generation. The gas was then engulfed in the melting pool because of the extremely fast cooling rates and solidification. In addition, substrate melting may be influencing the gas generation in the melting pool, especially throughout the graphite burning, enhancing the porous intensity.

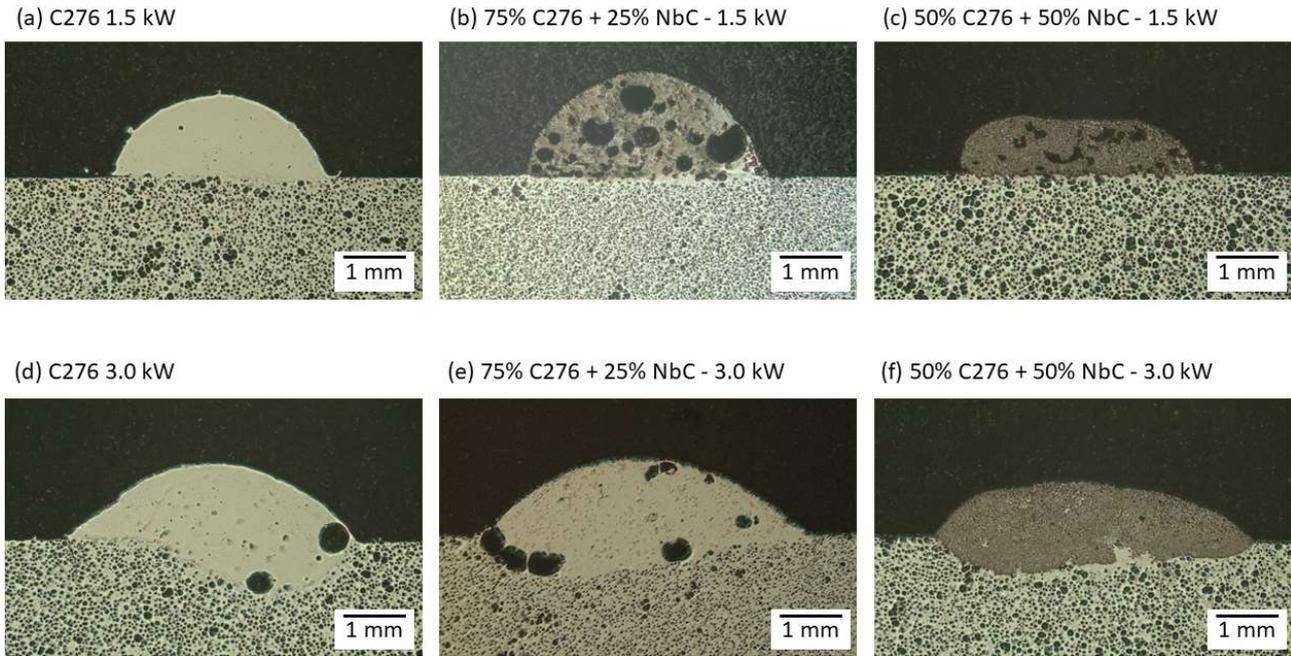


Figure 1. Macrographical analysis of the single-bead coatings.

Table 1. Single-bead geometry.

| Laser Power (kW) | 1.5 | | | 3.0 | | |
|-----------------------|------------------|-----|-----|-----|-----|-----|
| | NbC Feeding Rate | 0 | 25 | 50 | 0 | 25 |
| Height (mm) | 1.3 | 1.7 | 0.9 | 1.3 | 0.9 | 0.9 |
| Width (mm) | 3.4 | 3.8 | 3.7 | 4.6 | 5.2 | 5.1 |
| Wettability Angle (°) | 62 | 80 | 78 | 38 | 38 | 51 |

Regardless of the Laser power, the microstructure is comprised of Ni-FCC dendrites and interdendritic carbides for non-reinforced C276 alloy, as shown in Fig. 2a. Otherwise, it is easily seen that the higher burn-in-shape i.e., larger substrate melting lead to an increase in the volume fraction of interdendritic carbides (see dark phase, Fig. 2b)

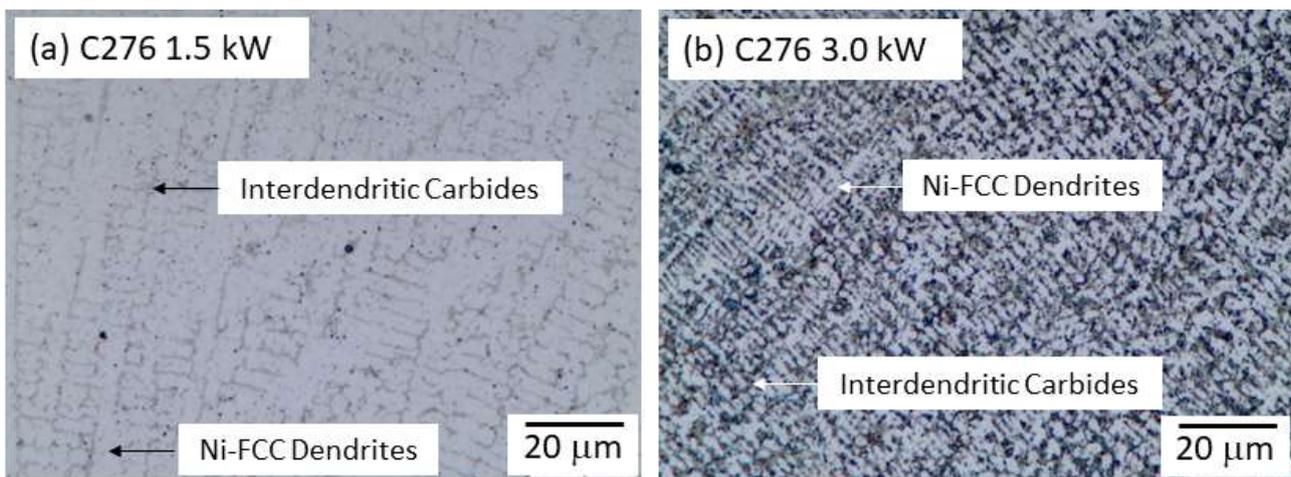


Figure 2. Microstructure of the Hastelloy C276 coatings.

The composites with 25% NbC feeding rate (1.5kW) showed a microstructure comprising unmelted particles of NbC and a large number of small nuclei of primary petaloid NbC, Ni-FCC dendrites, and interdendritic secondary carbides, as seen in Fig. 3a. On the other hand, the increase in the heat input induced a most pronounced NbC melting, showing only low volume of unmelted NbC particles and higher number of large primary NbC petaloid-like particles, as shown in Fig. 3b.

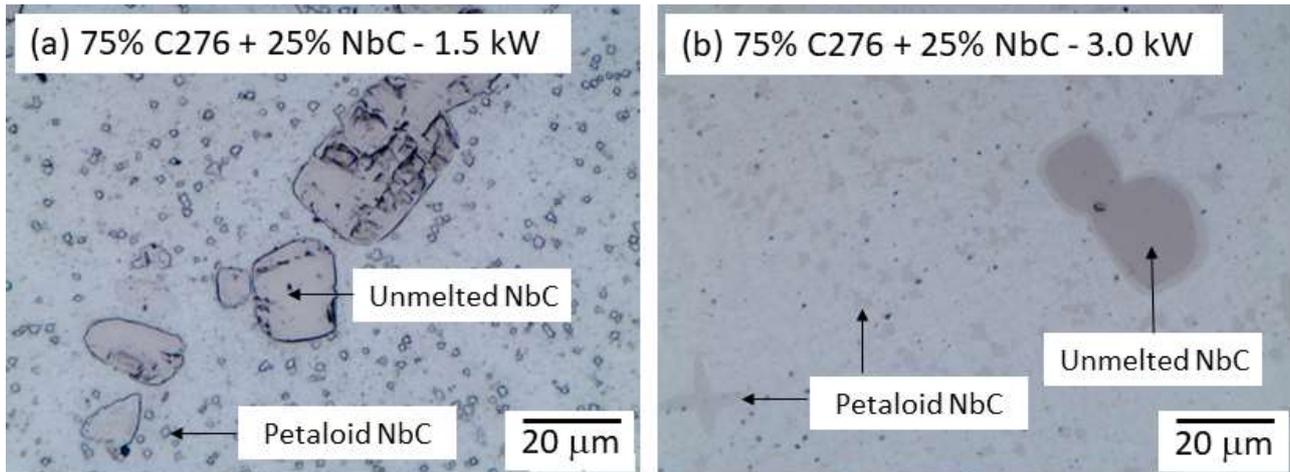


Figure 3. Microstructure of the Hastelloy C276 + 25% NbC composite coatings.

Furthermore, composites with a 50% NbC feeding rate (1.5kW) showed a microstructure comprising a large number of unmelted particles of NbC and only a bit coarsened primary petaloid NbC, Ni-FCC dendrites, and interdendritic secondary carbides, as seen in Fig. 4a. Otherwise, the increase in the heat input induced, once again, a most pronounced NbC melting, showing a noticeably high volume of large primary NbC petaloid-like particles, as shown in Fig. 4b. From the previous description, it seems clear that the adoption of 3.0kW is more effective on NbC particles melting and, consequently, the enhancing the NbC petaloid formation, delivering a most homogeneous microstructure than the low heat input evaluated here.

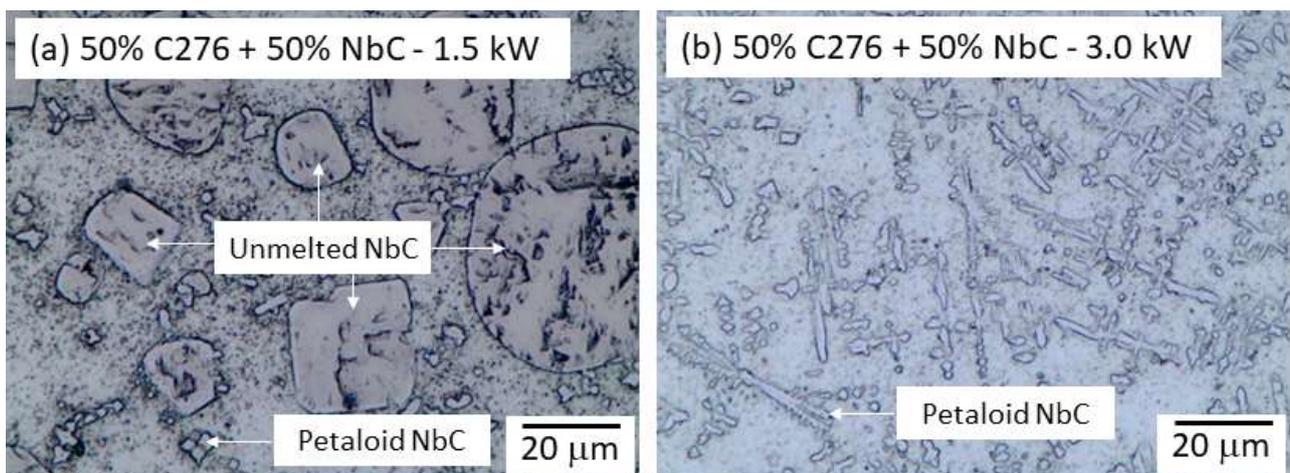


Figure 4. Microstructure of the Hastelloy C276 + 50% NbC composite coatings.

Dilution from 4 to 11% and 37 to 41% was measured for 1.5 and 3.0 kW, respectively. Hastelloy C276 showed hardness from 309 to 350 HV₂ whilst it ranged from 418 to 549 HV₂ for composite coatings. In any case, a higher NbC reinforcement feeding rate induced harder composite coatings as a consequence of the higher carbide volume fraction, as shown in Fig. 3. From the previous work (Pizzatto, *et al.*, 2021), the authors reported that a large dilution with AISI 304 L substrate had nullified the benefit of NbC reinforcement. Conversely, the present study revealed that dilution with the GGG40 ductile iron substrate showed only a minor influence on the hardness of composite coatings. It seems plausible to argue here that inside a large number of cladding variables in the composite synthesis, one must be considered is the substrate, not only due to the minor effect on hardness observed here but because the real chance to adopt higher heat input, leading to a most effective NbC particle melting and lower volume fraction of porosity in the coatings.

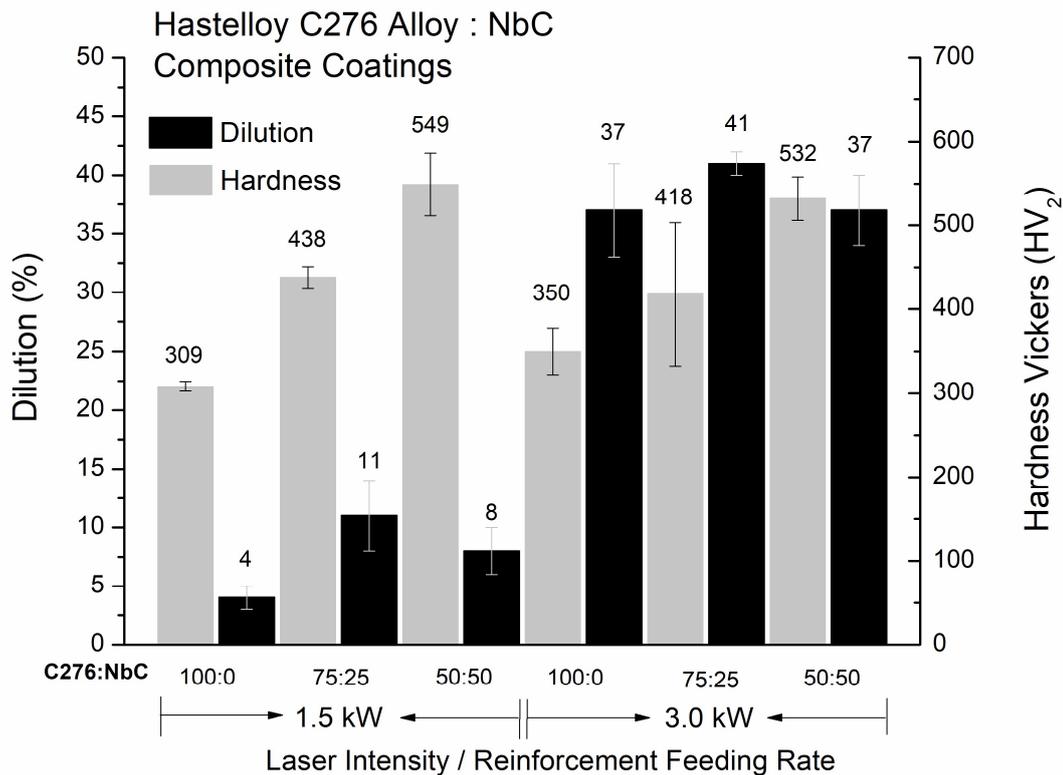


Figure 3. Hardness *versus* dilution with the substrate.

4. FINAL REMARKS

This work analyzed the bead geometry, defects, dilution, microstructure, and hardness of Hastelloy C276™ alloy as single-bead composite coatings by laser cladding. The main conclusions can be drawn:

- Lower bead width was obtained for coatings deposited with 1.5kW laser power, because of the gaussian energy distribution and concentration in the middle of spot size. Also, a higher wettability angle and higher clad height were measured at low heat input.

- The faster solidification cooling rates of coatings deposited with 1.5kW laser power induced a larger intensity of porosity, probably due to the prone tendency of gas engulfment into the melting pool. Contrasting to that as evidence, a lower amount of porous was retained in the melting pool for 3.0kW.

- Non-reinforced single-bead coatings processed with 3.0kW laser power showed higher dilution and, consequently, higher hardness than coatings deposited with 1.5kW. It was due to the substrate introduction of carbon and silicon, in turn, leading to a larger volume fraction of interdendritic carbides.

- Regardless of the heat input, composite coatings showed similar hardness at a comparable reinforcement feeding rate. It was because the high-carbon and -silicon substrate enhanced the carbide formation even for high dilution levels. At this rate, the choice of 3.0kW laser power seems an attractive option since lower porosity and the most pronounced NbC powder melting is observed, accounting for more homogeneous and promising composite coatings.

5. ACKNOWLEDGEMENTS

The authors thank SENAI Institute for Innovation (ISI Joinville) for the support of laser processing and characterization.

6. REFERENCES

- Abioye T.E., McCartney D.G., Clare A.T. Laser cladding of Inconel 625 wire for corrosion protection. *Journal of Materials Processing Technology*. 2015, March; 217: 232–240. Available from: <https://doi.org/10.1016/j.jmatprotec.2014.10.024>
- Ferreira L.S., Graf K., Scheid A. Microstructure and Properties of Nickel-based C276 Alloy Coatings by PTA on AISI 316L and API 5L X70 Steel Substrates. *Materials Research*. 2015, Jan; 18(1): 212-221. Available from: <http://dx.doi.org/10.1590/1516-1439.332914>

- Fernandes F., Cavaleiro A. and Loureiro A. Oxidation behavior of Ni-based coatings deposited by PTA on gray cast iron. *Surface and Coatings Technology*. 2012; 207:196-203. Available from: <http://dx.doi.org/10.1016/j.surfcoat.2012.06.070>.
- Graf K., *et al.* Effect of Dilution on the Microstructure and Properties of CoCrMoSi alloy Coatings Processed on High-Carbon Substrate. *Materials Research*. 2019, Jan; 22(1): e20180502, 1-7. Available from: <http://dx.doi.org/10.1590/1980-5373-MR-2018-0502>
- Haldar, B., Saha P. Identifying defects and problems in laser cladding and suggestions of some remedies for the same. *Materials Today: Proceedings*. 2018 Jun; 5(2): 13090–13101. Available from: <https://doi.org/10.1016/j.matpr.2018.02.297>
- Mankins W.L. and Lamb S. Nickel and nickel alloys. In: ASM International. *Properties and selection: nonferrous alloys and special-purpose materials*. Ohio: Materials Park; 1990. p.1363-1403.
- Pizzatto A., *et al.* Microstructure and Wear Behavior of NbC-Reinforced Ni-Based Alloy Composite Coatings by Laser Cladding. *Materials Research*. 2021, February; 24(3): e20200447, 1-7. Available from: <https://doi.org/10.1590/1980-5373-MR-2020-0447>
- Rivero L.E.H.S. Avaliação de Revestimentos de Superliga Hastelloy® C276 Depositados a Laser sobre Diferentes Substratos, 2019, UFPR, (M.Sc. dissertation). Available in Portuguese from: <http://www.prrpg.ufpr.br/pgmec/wp-content/uploads/2020/01/lubar.pdf>
- Rivero L.E.H.S., *et al.* Effect of Laser Power and Substrate on the Hastelloy C276TM Coatings Features Deposited by Laser Cladding. *Materials Research*. 2020, April; 23(2): e20200067, 1-7. Available from: <https://doi.org/10.1590/1980-5373-MR-2020-0067>
- Toyserkani E., Khajepour A., Corbin S. *Laser Cladding*. Washington: CRC Press; 2005. p.179-224.
- Venkatesh B., Sriker K., Prabhakar V.S.V. Wear Characteristics of Hardfacing Alloys: State-of-Art. *Procedia Materials Science*. 2015; 10:527-532. Available from: <https://doi.org/10.1016/j.mspro.2015.06.002>
- Zhong, M., Liu, W. Laser surface cladding: the state of the art and challenges. *Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science*. 2010; Feb; 224(5):1-20. Available from: <http://dx.doi.org/10.1243/09544062JMES1782>

7. RESPONSIBILITY NOTICE

The authors are responsible for the printed material included in this paper.