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WEAR BEHAVIOR OF INCONEL 625 COATINGS ON CARBON STEEL AND STAINLESS STEEL SUBSTRATES

Eliane Alves Kihara

Demostenes Ferreira Filho

José Lúcio Gonçalves Júnior

Goiás Federal University - School of Electrical, Mechanical and Computer Engineering (EMC) - Mechanical Engineering Building - Av. Ingá, Building B5 (in front of the rectory) Samambaia Campus, CEP: 74.690-900 - Goiânia – Goiás – Brazil

Eliane_kihara@discente.ufg.br, demostenesferreira@ufg.br, jlucio@ufg.br

Abstract. *The wear of stainless steel and carbon in coastal and offshore installations has been studied in order to increase the life service of engineering components and reduce maintenance costs. In this sense, the present work aims to present a literature review of different studies of wear behavior of Inconel 625 coatings applied on carbon steel substrate, 304L, 317L, Q235 and AISI 347 through thermally sprayed and hardfacing process to understand the wear behavior and the microstructure formed from the application of different coating techniques by inconel 625 on different substrates. Data was collected related to surfaces coated by Inconel 625 with wear test in saline solution with the objective to understand the influence of the coating process by Inconel 625 and the influence of the substrate on wear. The studies demonstrated that the wear behavior was characterized by means of a pin-on-disk device and abrasion test devices and the tests were carried out in NaCl solutions and DI water. It is observed in the literature that the variations of applied loads and slip speed (SS) had a smaller effect on the wear resistance of Inconel 625, the high hardness of the coating layer and the oxide film on the surface were responsible for the low wear rate. For stainless steel, carbon steel and medium carbon steel substrates, it is observed in the literature the presence in the coating layer of an anti-wear phase that considerably increases the resistance to wear by corrosion of surfaces coated with Inconel 625.*

Keywords: *Inconel 625, Wear, Corrosion, Coatings, Saline solution, Oxide.*

1. INTRODUCTION

The wear of stainless steel and carbon in coastal and offshore installations has been studied to increase the service life of engineering components and reduce maintenance costs. The surface properties of components can be improved by applying a protective coating layer on the substrate, thus extending the service life of parts subjected to harsh environments (Szymanski et al, 2015).

Zahrani and Alfantazi (2014) observed that Inconel 625, a Ni-based super alloy, is predominantly used for various overlay coating applications such as aviation, chemical industry, heat exchangers, marine industry, industrial boilers and also in critical industries such as aerospace, electrochemical, power generation plants, turbines, nuclear power plants due to excellent corrosion resistance with greater resistance, particularly at high temperatures.

Gurumoorthy et al. (2006) showed that Inconel 625 provides better properties on the substrate surface, improving hardness, toughness and increasing wear resistance with excellent adhesion. His resistance according to Dinda et al. (2009) is mainly due to the solid solution hardening effect of refractory metals, niobium and molybdenum, in a nickel-chromium matrix.

In this sense, this research aims to present a literature review of different studies of wear behavior of Inconel 625 coatings applied on carbon steel, stainless and medium carbon steel substrates by means of a thermal sprayed hardfacing process to understand the wear behavior and the microstructure formed from the application of different coating techniques by Inconel 625 on different substrates.

2. SURFACE COATING TECHNIQUES

According to Zahiri et al.(2014) surface coating can be performed by cladding, thermal spraying and hard coating. Throughout this section, the main processes studied and analyzed in Inconel 625 coating applications will be presented.

2.1. Thermal Sprayed

Among the various coating techniques currently used, thermal spraying is one of the most effective methods to increase component durability without changing substrate properties (Szymański et al., 2015). In this sense, the spray technique is used to coat various types of materials such as metals, ceramics, cermet, polymers and compounds.

According to Walsh et al. (2009) the advantage of the method is the substantial cost reduction compared to the use of bulk alloys.

The thermal spray technology can be divided according to the thermal energy source and the kinetic energy of the materials, so the technique is divided into flame spray (F), arc (A), plasma (P) and HVOF (H) (Li et al., 2013). Flame and plasma methods according to Li et al. (2013) are rarely used because they have complex processes, flame with reflow, and high cost in the case of plasma. Among the methods, the bow is the most used, as it guarantees an effective coating of large surfaces at a low production cost. The latest technology in the thermal spray coating technique is supersonic thermal spray which allows the production of high quality carbide coatings (Szymański et al., 2015).

Despite the various surface improvements arising from the application of the method in question, the surfaces coated by thermal spray can present microstructural defects, such as pores, microcracks and oxides within the coating layer, depending on the variation of the spray during deposition. This can considerably affect coating properties, however defects arising from the process can be eliminated by following proper procedures or spray guidelines (Bakere et al., 2015).

As thermal spraying is conducted by a heating process at high temperatures, the oxidation behavior of the spray material is considered to be a crucial factor influencing the microstructure and mechanical properties of the coating layer (Evangeline and Sathiya, 2019).

2.2. Hardfacing

Coatings are welded to the base material, low, medium carbon or low alloy steels, with the aim of protecting against abrasives or combining with materials for special applications (Wu and Tien Wu, 1997). Chandel et al. (1997) showed that hard coating is a potential overlap process and can produce layer thicknesses greater than other coating methods such as thermal spraying.

According to Wu and Tien (1997), the hard coating technology, in addition to preventing, can recover worn parts, prolonging their useful life. Compared to other conventional coating processes, such as galvanizing, galvanizing, thermal spraying, etc., hard coating has advantages as good adhesion and adequate thickness (more than 2.5 mm of a monolayer weld) to avoid wear and/or corrosion (Mendez et al., 2014). The wear performance of hard coatings is highly dependent on the surface alloy and thickness of the hard layers deposited.

The coating can be made by various welding techniques, such as metal gas arc welding (GMAW), oxyacetylene gas welding (OAW), tungsten inert gas welding (TIG), submerged arc welding (SAW) and welding shielded metal arc (SMAW). Among them, the most important differences are in soldering efficiency and solder plate dilution rates (Wu and Tien Wu, 1997). Although there are several types of welding processes for hard coating, gas arc welding is a more suitable method due to its higher deposition rate and reliability (Chandel et al., 1997). Thus, this work will present studies related to hard coating techniques by GMAW and CMT.

3. METALLURGY OF COATED SURFACES

According to Chen et al. (2020) the microstructure of 304L stainless steel surfaces coated by various thermal spray techniques exhibited a laminar structure due to the splats flattening mechanism during the solidification deposition process. During the SEM evaluation of the various specimens from the spraying techniques, the authors found the presence of layer structures with pores and oxides, microcracks formed along the coating-oxide interface or inside the oxide, where the porosity values and the quantity of oxides varied according to the applied coating technique, Figure 1. Chen et al. (2020) listed, in descending order, the porosity values of the samples according to the thermal spray technique in $A > P > F > H$, the specimen of the arc method exhibited the highest porosity among the other specimens, while by high-speed combustible oxygen exhibited the lowest. The oxide content in the coating varied according to the thermal spray technique and the gas used during the coating process in the order of $F > A > P > H$. In the present study, the results of microstructures, elemental mapping and SRD, EBSD and STEM examinations demonstrated that the oxides present in the coating layer were characterized as mainly Cr_2O_3 . Cr_2O_3 showed higher hardness but lower elasticity modulus than the Ni-based matrix, so the authors suggested that Cr_2O_3 was a hard disk and fragile phase within the cladding layer.

Already in works by Chen et al. (2016) the coating layer of the carbon steel surface coated with Inconel 625 by thermal arc spray consisted mainly of laminar structure, oxide layer and some pores. It was also detected that microcracks initiated and grew within the oxide layer or along the coating-oxide interface. On the other hand, the hardness measurements of the coating layer were directly related to the hardness of the raw material of the coating material.

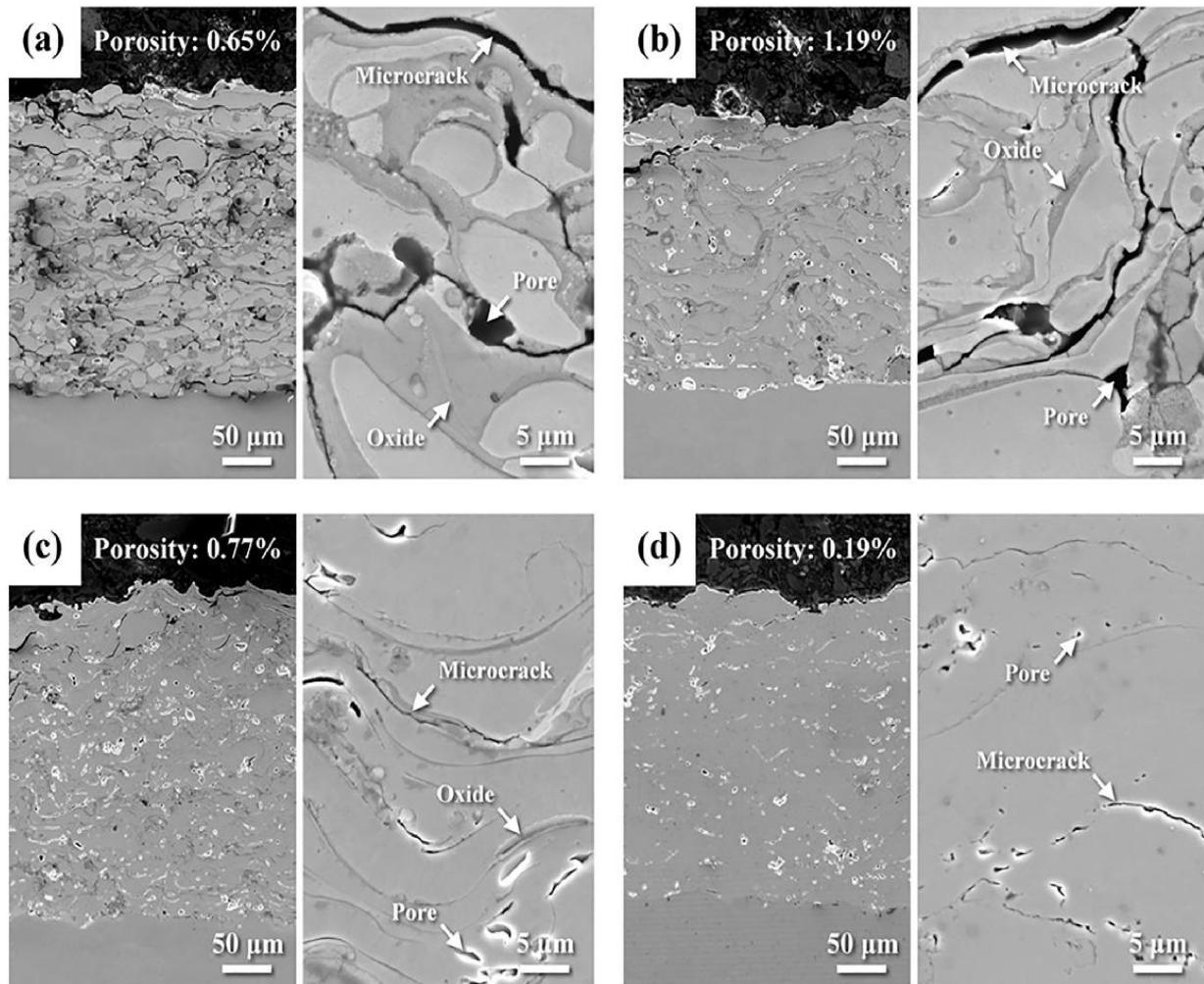


Figure 1. The cross-sectional microstructure of the Inconel 625 coatings prepared through various thermal spraying processes: (a) F, (b) A, (c) P and (d) H. (Chen et al.,2020)

During studies with AISI 316L surfaces coated with Inconel 625 by GMAW, Kumar and Shanmugam (2020) found that the hard coating microstructure consists mainly of columnar dendrites, equiaxed dendrites and unidirectional dendrites that were randomly solidified, Figure 2. They also observed changes in shape, grain size variation and different dendritic spacing due to the difference in the coefficient of thermal expansion between the substrate and the coated surface. In SEM micrographs and elemental mapping of the samples, the authors detected the presence of precipitates in the interdendritic regions in the overlap. The XRD plots also revealed the austenitic phase predominantly in the hard face and interface region, in addition to a slight increase in the ferrite phase in the interface region. In the microhardness values, the authors found a tendency to increase in the substrate region to the overlapping region due to the presence of alloying elements such as Ni, Mo and Nb in the interdendritic region.

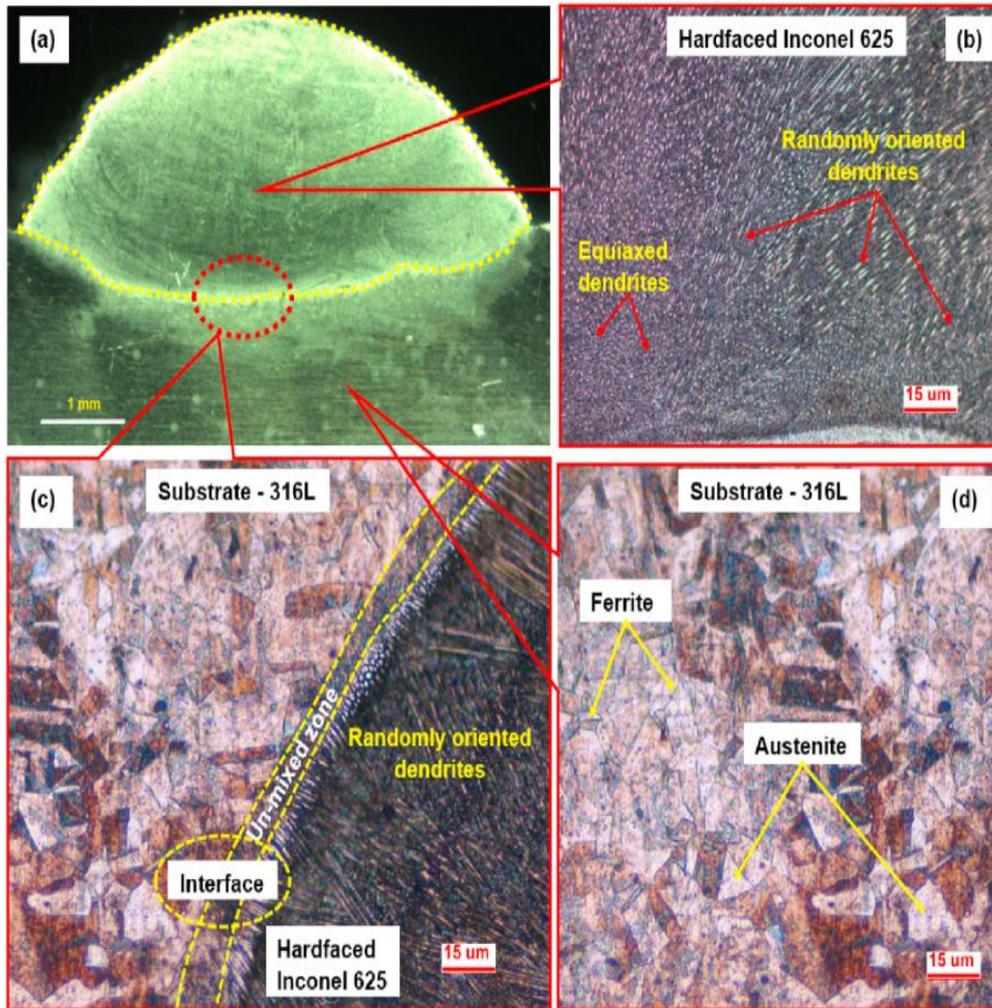


Figure 2. Macro and microstructure of hardfaced sample a) macrograph, b) hardfaced region, c) interface region and d) substrate. (Kumar and Shanmugam,2020)

In the works of Kajkumar et al. (2019) the hard lining of AISI 347 steel with Inconel 625 by GMAW, the micrographs, Figure 3, showed a superimposed weld microstructure composed mainly of columnar dendrites and dendrite spacing behavior and grain structures varying according to the parameters processing. The micrograph also shows phase rich in Nb and Mo in the interdendritic areas in the hard coating layer. Kajkumar et al. (2019) in the hardness tests verified a sharp drop in the entire interface of the coated sample and the surface rich in Ni phases γ (Ni, Fe), Ni, $M_{23}C_6$, Ni_3B and Ni_3Si carbides.

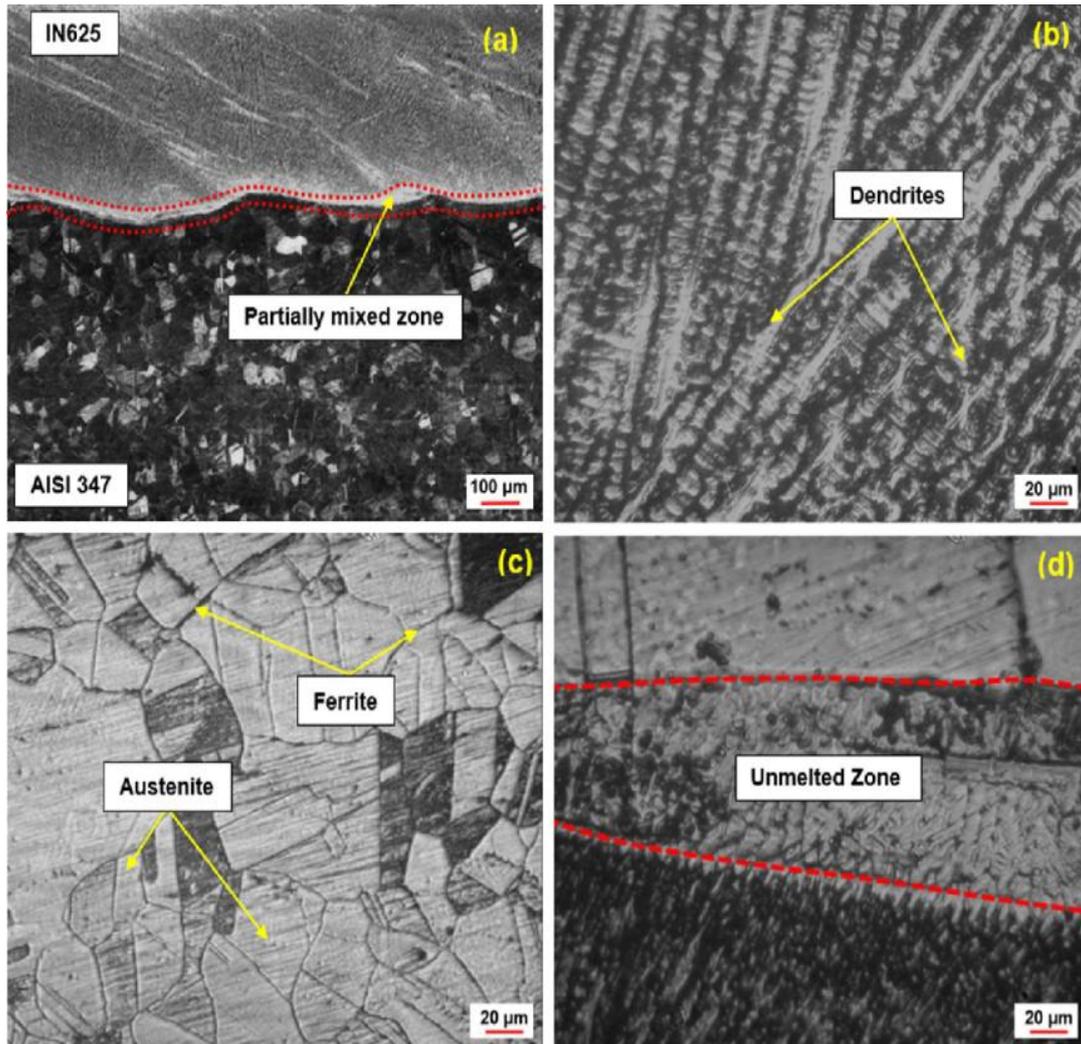


Figure 3. Microstructure of 150 A specimen at various locations. a IN625 hardfaced layer + substrate, b hardfaced layer, c AISI 347 substrate (Kajkumar et al.,2019)

In studies performed with Q235 steel surfaces coated with Inconel 625 by Cold Metal Transfer (CMT) Yangfan et al. (2019) identified different microstructures in the different layers of the coated samples. The lower layers consisted of thin primary cell structures, while the layers far from the interface the main structure became columnar dendrite with classical secondary dendrite arms and the last layer tended to form an equiaxed structure. Regarding hardness Yangfan et al. (2019) found an increase in the lower layer, then a reduction and an increase in the upper layer, they attributed the hardness variation to the displacement speed of the coating process.

In the works of Evangeline and Sathiya (2019) of 316L stainless steel surfaces coated with Inconel 625 by CMT, they detected that the clad bead microstructure is mainly composed of columnar, cellular dendrites with secondary dendritic arm spacing, Figure 4. The authors found that the changes in the shape and size of the grain structure and in the spacing of the dendrites were due to the variation in the parameters of the coating process. For hardness, they evidenced from the hardness tests that the coating and the interface have greater hardness than the base. The increase in hardness came from the enrichment of Inconel 625 of Mo, Cr, Nb and C. The maximum hardness of was attributed by the authors to the formation of equiaxed dendrites due to the higher amounts of Nb.

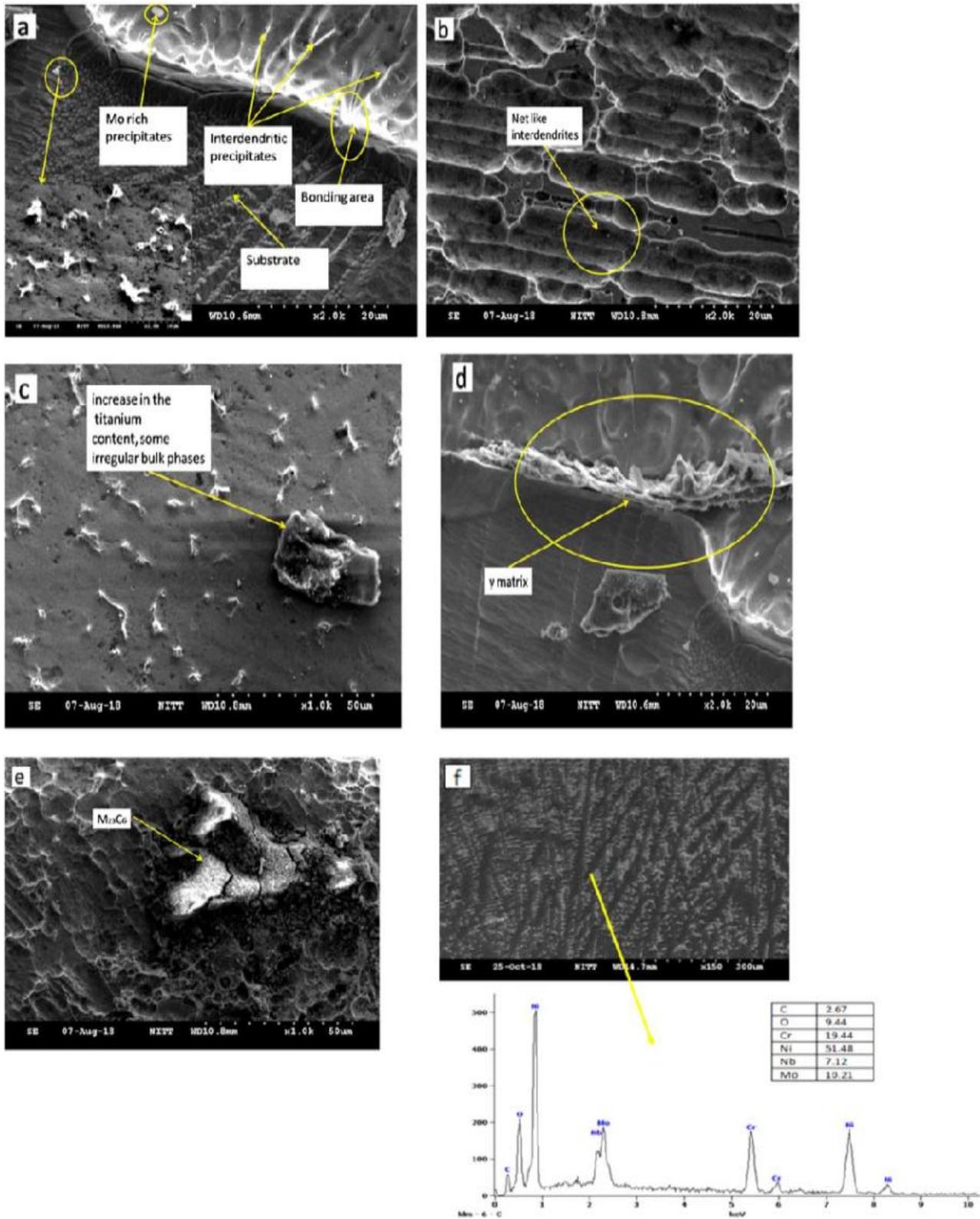


Figure 4. (a)–(f) SEM micrographs of the clad interface region.
 (Evangeline and Sathiya ,2019)

Thus, all coating processes by GMAW and CMT presented microstructures mainly of columnar dendrites while the thermal spray method presented mainly laminar microstructures. All methods presented demonstrated increased hardness of the coated layer compared to the substrate.

4. DISCUSSION

In the pin-on-disk wear tests in saline solution and DI water of stainless steel 304L coated with Inconel 625 by various thermal spray processes with a normal load of 10N and a slip speed (SS) of 0.3 m/s, Chen et al. (2020) found that despite the test conditions, weight losses of all specimens increased with increasing wear distance. Chen et al. (2020) also found that the various thermal spray techniques have a similar order of weight loss in a test in 5%wt NaCl solution and in DI water, where $F < A < P < H$, Figure 5. However, the weight loss of specimens from the various thermal spray techniques tested in DI water were higher than those tested in 5%wt NaCl.

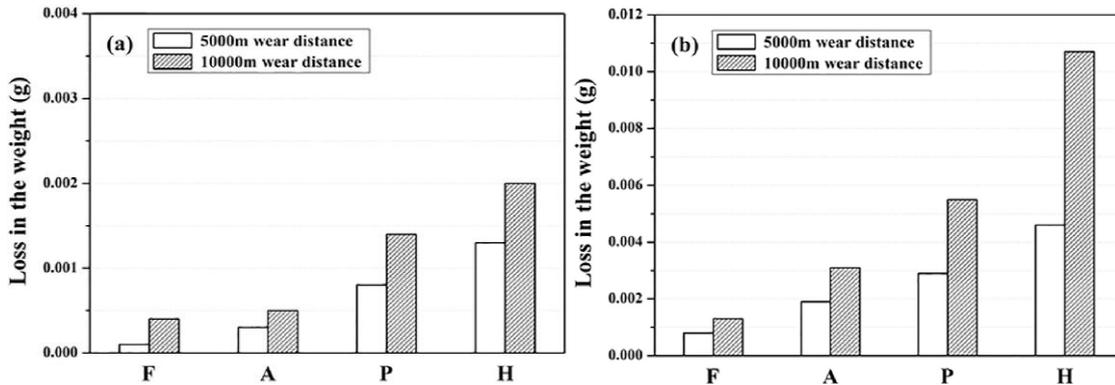


Figure 5. Loss in the weights of various Inconel 625 coating specimens wear tested in the (a) 5 wt% NaCl solution and in (b) DI water. (Chen et al., 2020)

In the works of Chen et al. (2016) the Inconel 625 sample revealed superior hardness and an oxide film free surface compared to the Zn / 15Al and Al samples. The wear rate and COF of the tested sample in deionized water showed little change compared to the tested sample in NaCl solution, Figure 6. The authors speculated the Inconel 625 specimen's polishing and wear mechanism was the main reason for the low wear rate and COF of the coating layer.

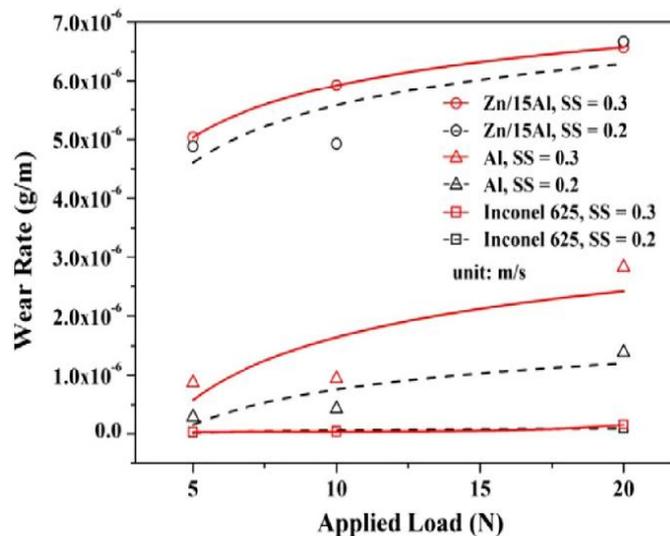


Figure 6. The relation between applied load and wear rate of various coating specimens. (Chen et al., 2016)

In abrasive wear tests conducted at varying temperature for 1 hour by Kumar and Shanmugam (2020) with AISI 316L surfaces coated with Inconel 625 by GMAW at speed of 600 rpm with 10 cycles per second, load of 50 N and 130 N, distance 1000 m slide, 280 g/min silica sand hopper (SiO₂) of size 200-500 μm verified that the wear mechanisms observed on the worn surfaces of the hard coating samples revealed micro-plows, shallows and grooves. The authors also detected deeper and longer grooves in the substrate samples, while the hard-coated samples improved wear characteristics, both reciprocating and three-body abrasive wear, Figure 7. As for the alternative wear test at elevated temperature, the

authors found better wear resistance due to the formation of oxide that helped to avoid metal-to-metal contact, therefore, better wear properties. The wear mechanism of the test was identified as abrasive type followed by oxidation wear. Thus, Kumar and Shanmugam (2020) concluded that the abrasive wear resistance of the superimposed specimen was remarkably higher than that of the substrate in terms of specific wear rate. The wear tracks of the hard-coated specimen exhibited microplow, microcorrosion and microcut mechanisms in both load cases.

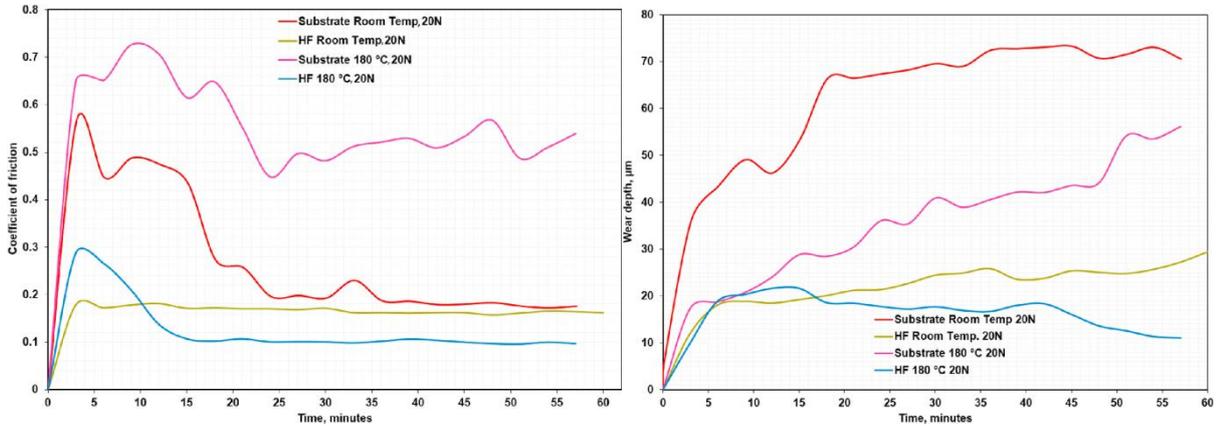


Figure 7. Wear Depth vs. time plot - comparison between substrate and hardfaced sample at different conditions and Coefficient of friction vs. time plot - comparison between substrate and hardfaced sample at different conditions. (Kumar and Shanmugam,2020)

In pin-on-disk wear tests carried out by Kajkumar and Kannan (2019) on AISI 347 steel surface coated with an Inconel 625 with 30, 60 and 90N loads, sliding distance 3000m, speed 200,400 and 600 rpm and sliding time 90,60 and 30 min verified that the Inconel 625 coating during load conditions of 90 N, the wear trend increased compared to 30 N and 60 N. At loads lower than 30 N, abrasive type wear is observed, while that at 90 N, oxidation is observed, Figure 8 and 9. Thus, the authors showed that from the pin-on-disk test that the wear mechanism differs with the applied load and sliding time, Figure 11.

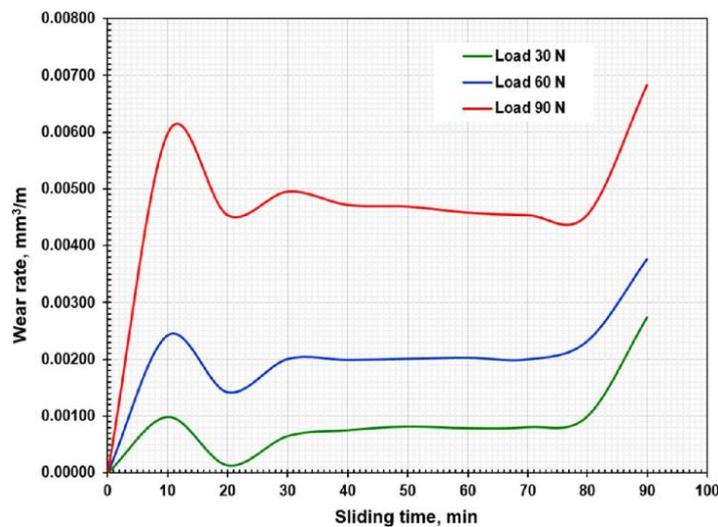


Figure 8. Typical wear rate versus sliding time of Inconel 625 worn surface under various loads. (Kajkumar and Kannan ,2019)

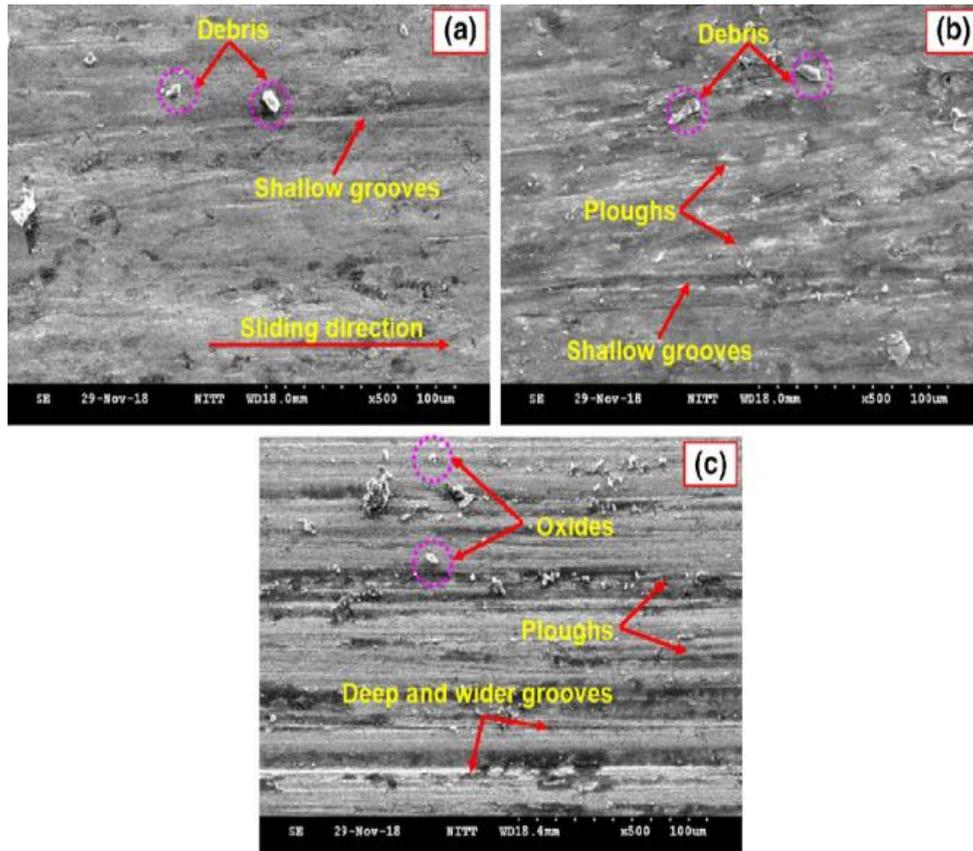


Figure 9. SEM micrographs of the wear track highlighting the debris formation of the worn surface.
(Kajkumar and Kannan ,2019)

Pin-on-disk wear tests was carried out by Evangeline and Sathiya (2019) on 316L stainless steel surfaces coated with Inconel 625 by CMT with 20.50 and 90N loads, sliding distance 3000 m, speed 200.400 and 600 rpm and sliding time 90, 60 and 40 min verified that as deposited in the coating of Inconel 625 composed of the γ (Ni, Fe) phases rich in Ni, $M_{23}C_6$, Ni_3B and Ni_3Si . in the 90 N load, the wear rate doubles in relation to the 20 N and 50 N loads. The authors also found that, by applying the 20 N load, the adhesive wear is formed, whereas, by the application 90 N, oxidation areas were observed. The authors concluded that the wear mechanism varies with time of use and applied load.

5. CONCLUSIONS

In the investigations presented regarding several processes of coating of inconel 625 on different types of substrates, the following inferences can be presented:

- According to the studies by Chen et al.(2020) and Chen et al.(2016) with spray coating techniques, it was observed that both the 304L stainless steel and the carbon steel substrates presented a mainly laminar microstructure of the samples of thermal spray coating of inconel 625. Both authors found the presence of layer structures with pores and oxides, microcracks formed along the oxide-coating interface or inside the oxide, where the porosity values and the amount of oxides varied according to the applied coating technique.
- In the studies presented on Inconel coating by GMAW Kumar and Shanmugam (2019) and Kajkumar and Kannan (2020) found hard coating microstructures that have mainly columnar dendrites for both substrates. Also in the two studies mentioned, they identified that the grain structures varying according to the processing parameters
- For the CMT method, the studies cited for 316L and Q235 steel found hard clad microstructures that have mainly columnar dendrites with secondary dendrite arms(Kajkumar and Kannan ,2019) and (Evangeline and Sathiya ,2019)
- In all the studies presented, the tests performed indicated that the wear behavior of the coating layer was determined by the hardness of the coating layer and the characteristics of the oxide film formed on the worn surface (Chen et al.,2020)
- All methods presented demonstrated increased hardness of the coated layer compared to the substrate.
- As for the spray coating technique in studies presented by Chen et al. (2020) the weight loss reduced according to the applied spraying process.

- In the studies by Chen et al. (2016) proved that inconel coating has greater wear resistance compared to other materials such as Zn, 15Al and Al.
- Kumar and Shanmugam (2020) proved that at high temperatures better wear resistance is obtained due to the formation of oxide that help to avoid metal-to-metal contact, therefore, better wear properties and also showed that the abrasive wear resistance of the overlaid sample was notably higher than substrate in terms of specific wear rate AISI 316L coated with Inconel 625 by GMAW.
- Kajkumar and Kannan (2019) and Evangeline and Sathiya (2019) proved that the wear mechanism differs from the surfaces coated with Inconel 625 made of AISI 347 and 3016L steel with the applied load and slip time.
- All studies presented have proven the effectiveness of the Inconel 625 coating in increasing corrosion-wear resistance. The results indicated that the wear behavior of the coating layer was mainly determined by the hardness of the coating layer and the characteristics of the oxide formed on the worn surface. Thus, the high hardness of the coating layer and an oxide-free surface film were responsible for the low wear rate, while the corrosion resistance was determined by the characteristics of the oxide formed on the surface.
- In studies using thermal spraying as a coating method, it is noted that the oxides formed on the coating surface as Cr₂O₃ presented a higher hardness which suggested that oxide within the coating layer functioned as an anti-wear phase against the corrosive-wear environment, considerably increasing the corrosion-wear resistance.
- In studies with CMT coating, the presence of higher chromium and molybdenum content in Fe-Ni-based alloys increases corrosion resistance. Corrosion resistance depends on the dendritic arm gap, where the thin dendritic arm gap offers better corrosion resistance. Thus, the coated area exhibits the best corrosion performance.
- In studies with GMAW coating, the presence of precipitates rich in Mo and Nb increases corrosion resistance. Thus, the coated area exhibits the best corrosion performance.
- Based on this literature review, it is observed that there is potential for studying the coating with applications of Inconel 625 on carbon steel substrate, using the GMAW process with different types of shielding gases and verifying the influence of these gases, as well as possible heat treatments, in wear resistance.

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