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Experimental Investigation on the Coating of Nickel-Base Super Alloy Using Wire Flame Spraying

Noureddine MENASRI[1], Said ZERGANE[1], Noureddine AIMEUR[1], Abdelhamid SACI[2]

[1] University Mohamed Boudiaf of M'sila, Algeria
noureddine.menasri@univ-msila.dz, http://orcid.org/0000-0002-7373-684X
said.zergane@univ-msila.dz, https://orcid.org/0000-0002-2800-6186
noureddine.aimeur@univ-msila.dz, https://orcid.org/0000-0003-0293-8417
[2]Maintenance Equipments Industrial (M.E.I) M'sila, plasma service, Algeria
hamidahmed3361@yahoo.fr

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Abstract: Inconel738 is a nickel-based super alloy widely used in manufacturing gas turbines, particularly in the manufacture of blades that are in direct contact with hot gases during their operation. As a result, these blades are subjected to high temperatures, significant static and dynamic stresses, erosion and/or hot corrosion which can be very severe. The use of coatings is one of the most effective strategies to protect materials against corrosion and increase the wear resistance of materials. In this study, β-Ni-Al coatings were sprayed onto an Inconel738 substrate using a wire flame spraying process and characterization of coating has been made.

Keywords: Nickel-based super alloy, wire flame spraying, XRD diffraction, microhardness, microstructure.

1. Introduction

Gas turbines are complex machines in which mechanical and thermal effects strongly interfere, at high stress levels for long operating times. To tackle this problem, specific materials of high technological degree have been developed, capable of satisfying these extreme loading conditions, among them nickel super alloys.

Nickel super alloys have good mechanical resistance at high temperatures. The latest developments in these materials seem to indicate that the exceptional level of performance they achieve will no longer be significantly improved with new compositions.

The only limited gains that can be achieved are through the deposition of coatings. Among these, we identify thermal spraying which allows the formation of protective coatings against wear, temperature, corrosion, etc. [1-8].

Thermal spraying is a method of surface treatment by coating combining various techniques, namely oxyacetylene flame spraying [9-13], high-velocity spraying (HVOF) [14-20], electric arc spraying [21-23], atmospheric plasma spraying [24-28] and the cold spray process [29]. The different thermal spraying processes are defined mainly by the energy source used (combustion, electric discharge). The process is conditioned by thermal and/or kinetic transfers between the sprayed material and the enthalpic source used. The kinetic energy is communicated to the particle by the speed and viscosity of the projecting gas mixture. The coating construction results from the stacking of the particles on the substrate. The balance between the kinetic and thermal energy of the particles is therefore paramount to the quality of the coating. The coating is mainly characterized by the adhesion to the substrate, the porosity levels, and the oxide content. In general, the higher the particle velocity, the better the adhesion and the lower the oxide content of the coating [30].

In recent years, a lot of development and research work has been done in the field of thermal spray coating applied on nickel super alloys to improve the surface properties.

According to Sushila Rani et al. [31], a gas turbine blade failure occurs due to the combined effect of surface degradation caused by overheating, oxidation, hot corrosion, and degradation of the highly oxidized coating. M. F. O. Schiefler Filhon et al. [32] studied the influence of spraying parameters. The variation of spray parameters had a great influence on the quality of X46Cr13 stainless steel coatings. This fact could be demonstrated by the large variation obtained in terms of microstructural characteristics, mechanical properties, and corrosion performance. Xueyuan Gong et al. [33] studied the microstructure evolution of a NiAl coating and its underlying single crystal super alloy substrate by EB-PVD. The deposited NiAl coating displayed a columnar microstructure with a preferred orientation (110). Kirkendall voids were formed in the NiAl coating, indicating the different diffusion coefficients of the elements in the coating and the substrate. Equiaxed β-NiAl grains were developed in the inter-diffusion region after diffusion annealing at 1100 ° C for 10 h, which showed different orientations of crystalline grains in the coating and substrate.

M. Kopec et al. [34] concluded that the aluminized layer can significantly improve the creep performance of nickel super alloy. It has been shown that the application of such a layer can effectively protect the raw material from processes such as oxidation, hot corrosion, or wear, and thus prolong its service life. TF An [35] focused on the effect of alumina formation and transformation on the oxidation behavior of a nickel-based super alloy with an aluminide diffusion coating. This coating improved the oxidation resistance. The oxidation kinetic curve of the nickel-based super alloy at 1000°C was slightly higher than that at 1050°C within the first 100 hours. This abnormal phenomenon is attributed to the high amount of W and Mo (about 12%). The growth stress was characterized by the formation of convoluted scales.

The β-NiAl coatings have been widely used as metal protector coatings to protect the underlying super alloy from high-temperature oxidation. D.B. Miracle [36] presented a critical review of the physical and mechanical properties of NiAl.

2. Materials and Experimental Procedures

2.1. Materials Used

The substrate used in our study is the nickel-based super alloy / Inconel 738 which is used for the manufacture of the moving blade of a gas turbine, where the detection of the chemical composition of Inconel 738 has been made by using a portable analysis device Thermo scientific NitonXL 3t. The chemical composition is shown in Table 1.

Table 1: Chemical composition of Inconel738(%weight)

	Se	Mo	Nb	Zr	W	Cu	Ni	Co	Fe
Inconel 738	0.012	1.670	0.786	0.017	2.419	1.017	59.688	8.396	0.357
	Mn	Cr	V	Ti	Al	C	B	Ta	
Inconel 738	0.078	16.023	0.043	3.269	3.4	0.10	0.001	1.75	

The Ni-Al wire, whose chemical composition is shown in Table 2, has been sprayed onto an Inconel 738 substrate using a wire flame spraying technique.

Table 2: Chemical composition of Ni-Al wire (% weight)

Al	Si	Fe	Ni	Cu	Zr
98,034	0,641	0,727	0,351	0.215	0,032

Prior to the coating process, the substrate surface has been sandblasted with grains of sand type NK F080. The purpose of this step is to remove oxides from the surface and create a roughness profile for a good adhesion of coating.

2.2. Processes and Coating Conditions

Ni-Al layers of 3 mm thickness have been deposited on Inconel 738substrate using thermal spraying technique with Metco gun (*Fig. 1*). Oxyacetylene flame was used in the case of wire flame spraying because of the high temperatures offered by the combustion of these gases. The flame could be easily adjusted to become an oxidizing, neutral or reducing flame. A neutral flame was obtained by adjusting the acetylene flow rate. The coatings have been carried out at the Industrial Equipment Maintenance Company M'sila (MEI), Algeria.

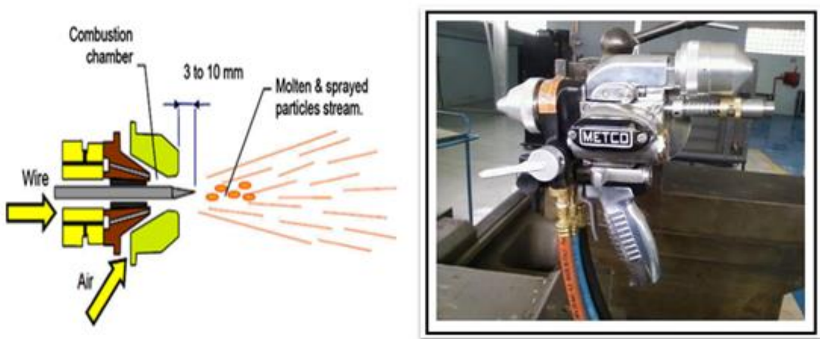

Figure 1: Operating diagram of a wire flame gun

The projection parameters are summarized in Table 3.

Table 3: Coating deposition parameters

Projection parameters	
Acetylene pressure	7 kPa
Oxygen pressure	14.7 kPa
Air pressure	33.6 kPa
Acetylene flow rate	39 L/min
Oxygen flow rate	44 L/min
Air flow rate	52 L/min
Wire diameter	3.2 mm
Spraying distance	100-200 mm
Particle velocity	150 m/s

2.3. Characterization Methods

The coated samples have been cut to a size of 15×10×2 mm^3 using a wire cutter, mounted in a cold epoxy resin, polished with abrasive papers (roughness from 200 to 5000), followed by a very fine finish polishing with an Al_2O_3 alumina powder having a grain size of 0.3µm, suspended in water on a silk cloth. Finally, the coated samples were cleaned in distilled water and dried in hot air.

Several tests were carried out in collaboration with industrial Algerian companies namely X-Ray diffraction analysis, micro hardness, and microscopic examination for the characterization of the coating.

X-ray diffraction patterns have been recorded using a PANALYTIC X'PERT PRO diffractometer equipped with a Ni filter and a copper anticathode using Kα radiation of wavelength $\lambda = 1.5406$ Å. The working conditions are: U = 30 kV and I = 25 mA, the sweep angle $2\theta = 10 – 80°$ with a speed equal to 0.05 °/s. The samples have dimensions (10×10×2 mm^3).

Identification of the phases present in the compound has been done using micro informatics with the help of X'Pert High Score plus software (JCPDS files).

The Vickers micro-hardness measurement was performed on polished cross-sections of coatings using a Tukon Microhardness 2500 Wilson Hardness under a load of 25 g during 10 seconds. The measurement points in each zone of the section are spaced at about 0.5 mm.

The deposited coating microstructures of the cross-sections of the samples after etching in Nital 3% have been observed using optical microscopy reflection OLYMPUS BH2 in order to investigate the morphology of splatters, porosity and micro cracks [37].

3. Results and discussion

3.1. XRD Diffraction

Fig. 2 shows the X ray diffraction spectrum obtained for the (Ni-Al) coatings, performed by wire flame spraying process on an Inconel 738 substrate.

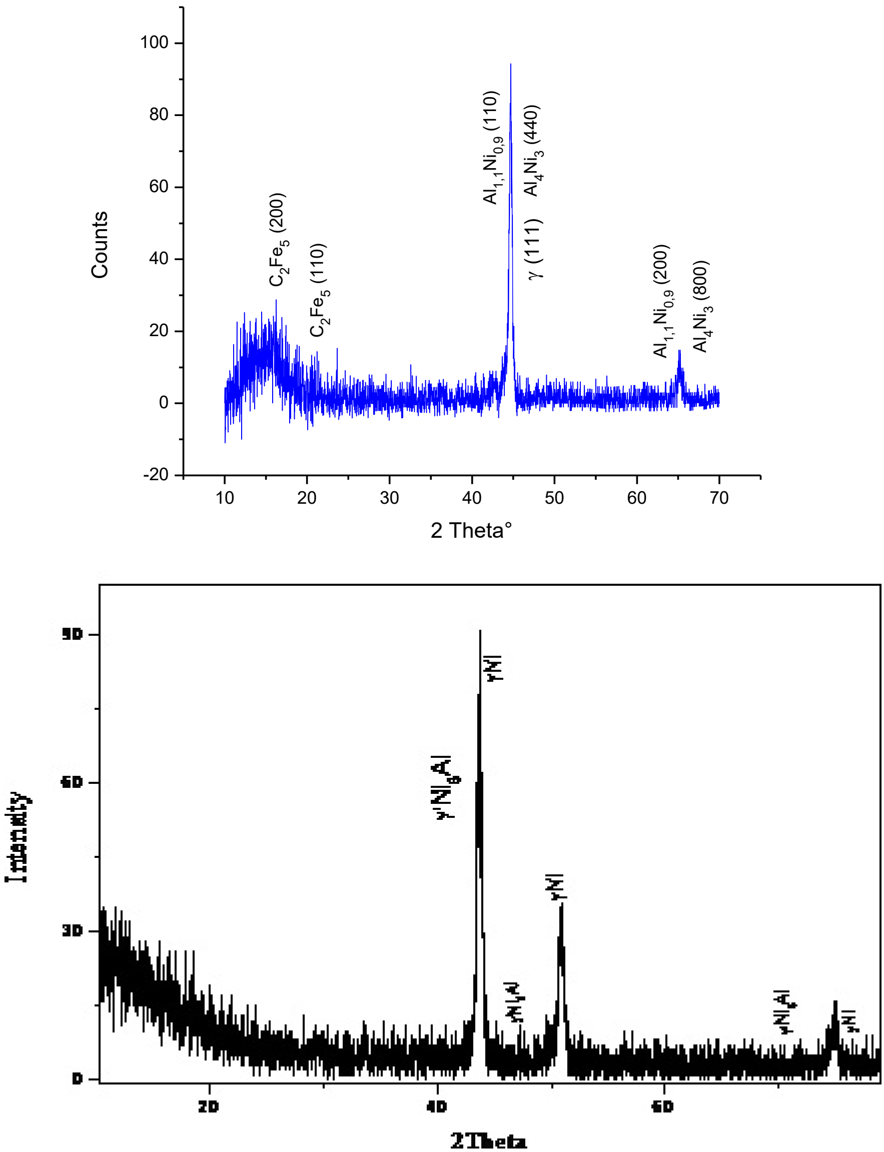

Figure 2: X ray diffraction spectra of the (Ni-Al) coating, performed by wire flame spraying process on Inconel 738 substrate

The X-ray diffraction diffractograms show the main peaks characteristic of the super alloy such as the γ matrix (JCPDS n°96-901-3033) and the γ′ precipitate phase (Ni_3Al) (JCPDS n°0021-0008). The formation of the γ′ precipitate phase is ensured by the reaction of the Nickel atoms with the Aluminum atoms of deposits. The very strong coherence between γ/γ' confers a very high hot mechanical strength of nickel-based super alloys. In addition, peaks of iron carbide (Fe_5C_2) of monoclinic crystalline structure with crystalline parameter equal to 11.5620 Å (JCPDS N° 01-089-2544) are observed. The formation of this carbide is ensured by the reaction of the iron atoms with the carbon atoms. The carbide is responsible to increase coating hardness and wear resistance.

3.2. Microhardness

Fig. 3 shows the micro hardness distribution in a cross-section of the coating obtained by flame spraying of Ni-Al wire on Inconel 738 substrate. The curve shows clearly that the coating is harder than the substrate. The nickel-aluminum alloy coating has a small variation in micro hardness from the first measuring point to the fifth point. The maximum is equal to 488HV at the 4rd measurement point and the minimum is equal to307HV at the first measurement point. Micro hardness is very dependent on the nature and the distribution of the phases in the coatings-substrate. The hardness of the substrate is almost stable along the investigated area.

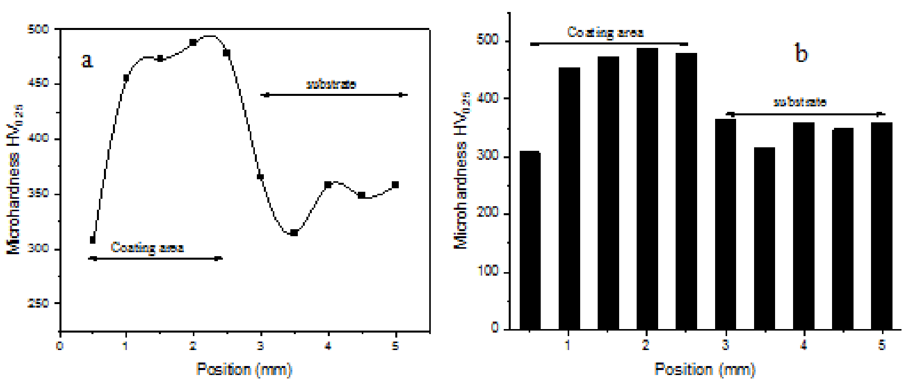

Figure 3: (a) Distribution of the Vickers micro hardness values, measured in the cross-section of the coatings / substrate domain and (b) histogram representation

3.3. Coating Microstructure

The microstructure of thermally sprayed coatings, which results from the solidification and sintering of the particles, often contains pores, oxides and cracks.

Fig. 4 shows the cross-section view of the coating wire flame spraying (Ni-Al) on substrate Inconel 738, which contains several dispersed phases: the major phase γ matrix, the γ′ precipitate phase (Ni_3Al) deformed from different directions with remarkable intensities and a small amount of carbides.

The presence of certain types of pores has been observed. The low particle velocity of the thermal spraying flame process has the effect that the certain particles are not well dispersed during the impact on the substrate. Therefore, this phenomenon favors the presence of pores in the coating. However, no crack has been revealed. The profile interface appears to adhere to the substrate.

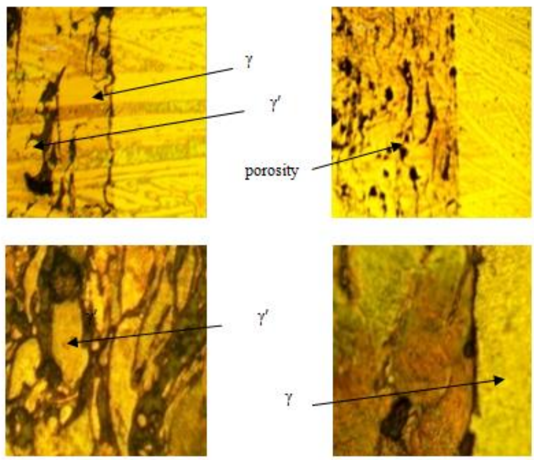

Figure 4: Optical imaging of the samples investigated by using a metallographic microscope: the selected pictures indicate the cross-section images taken from a limited area of the transition domain between Inconel super alloy substrate and the Ni-Al coating / substrate

4. Conclusion

Nickel-based alloys hardened by precipitation of the phase (γ') used in the blades of gas turbines are very complex materials. Exposed to high temperatures during service, their high temperature strength and endurance are unmatched by any class of alloy.

Improving the performance of gas turbines is an important issue, which requires identifying and understanding the deterioration mechanisms that take place during their use. In the hottest parts of gas turbines (i.e. combustion chamber), the materials used are subjected to high thermal and mechanical stresses. This is particularly the case of turbine blades. The temperatures of use are indeed, of the order of 800 °C. These stresses induce different types of degradation. The most frequently encountered by turbine blades are erosion, creep, fatigue, corrosion and oxidation.

In order to improve the high temperature durability of the turbine blades, coatings are made by thermal spraying with flame - wire (Ni-Al), deposited with the thermal spraying systems Metco.

From the characterizations by optical microscopy, micro-hardness measurements and the X-ray analysis, the following main results have been obtained:

- The presence of several distinct phases, which gives a heterogeneous structure. The phases revealed have compound, and elemental types. We can observe the presence of Ni_3Al (γ'), carbides, and the Nickel (γ) matrix.
- The adhesion of the flame wire coating is less acceptable, with the existence of pores.
- The micro hardness of the wire flame coating is higher than that of the substrate. This can be explained by the formation of the hardening phase of Ni_3Al with a significant increase of micro-hardness.
- We can confirm that wire flame spraying remains an effective solution in ordinary industrial applications where there is no high precision requirement to extend the life of the equipment without increasing the cost of the latter.

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References

[1] Mudgal, D., et al., "Corrosion behavior of bare, Cr3C2-25%(NiCr), and Cr3C2-25%(NiCr)+ 0.4% CeO2-coated superni 600 under molten salt at 900° C", *Journal of materials engineering and performance*, Vol. 23, no. 11, pp. 3805–3818, 2014. DOI: https://doi.org/10.1007/s11665-014-1177-3.

[2] Kumar, S., et al., "Cyclic oxidation behavior of bare and Cr3C2-25 (NiCr) coated super alloy at elevated temperature", *Adv. Mater. Lett*, Vol. 4, no. 10, pp. 754–761, 2013. DOI: https://doi.org/10.5185/amlett.2013.2428.

[3] Yang, Q., Xing, A., and Zhanqiang, L., "Machining performance and tool wear of coated carbide inserts in high speed turning powder metallurgy nickel-base superalloy", in *2010 WASE International Conference on Information Engineering*, IEEE, 2010, pp. 71–74.

[4] Mazur, Z., et al., "Failure analysis of a gas turbine blade made of Inconel 738LC alloy", *Engineering failure analysis*, Vol. 12, no. 3, pp. 474–486, 2005. DOI: https://doi.org/10.1016/j.engfailanal.2004.10.002.

[5] Li, S.-L., Qi, H.-Y., and Yang, X.-G., "Oxidation-induced damage of an uncoated and coated nickel-based superalloy under simulated gas environment", *Rare Metals*, Vol. 37, no. 3, pp. 204–209, 2018. DOI: https://doi.org/10.1007/s12598-017-0931-8.

[6] Alidokht, S. A. and Chromik, R. R., "Sliding wear behavior of cold-sprayed Ni-WC composite coatings: Influence OF WC content", *Wear*, Vol. 477, pp. 203792, 2021. DOI: https://doi.org/10.1016/j.wear.2021.203792.

[7] Gibson, G., et al., "Influence of shot peening on high-temperature corrosion and corrosion-fatigue of nickel based superalloy 720Li", *Materials at High Temperatures*, Vol. 33, no. 3, pp. 225–233, 2016, DOI: https://doi.org/10.1080/09603409.2016.1161945.

[8] Aouici, S., et al., "Corrosion Resistance of Coatings Produced by Spraying Powders Under a Laser Beam in a Saline Environment NaCl 3% by the Electrochemical Method", *Acta Universitatis Sapientiae, Electrical and Mechanical Engineering*, Vol. 12, no. 1, pp. 105–116, 2020.

[9] Rachidi, R., El Kihel, B., and Delaunois, F., "Microstructure and mechanical characterization of NiCrBSi alloy and NiCrBSi-WC composite coatings produced by flame spraying", *Materials Science and Engineering: B*, Vol. 241, pp. 13–21, 2019. DOI: https://doi.org/10.1016/j.mseb.2019.02.002.

[10] Redjdal, O., et al., "Characterization of thermal flame sprayed coatings prepared from FeCr mechanically milled powder", *Journal of Materials Processing Technology*, Vol. 213, no. 5, pp. 779-790, 2013, DOI: https://doi.org/10.1016/j.jmatprotec.2012.11.018.

[11] Amokrane, B. M., et al., "Microstructural and mechanical properties of Ni-base thermal spray coatings deposited by flame spraying", *Metallurgical and materials transactions B*, Vol. 42, no. 5, pp. 932–938, 2011, DOI: https://doi.org/10.1007/s11663-011-9551-0.

[12] Bradai, M. A., et al., "Study of microstructure, phases and microhardness of metallic coatings deposited by flame thermal spray", *Journal of Materials Processing Technology*, Vol. 200, no. 1–3, pp. 410–415, 2008, DOI: https://doi.org/10.1016/j.jmatprotec.2007.08.048.

[13] Lunn, G. D., Riley, M., and McCartney, D., "A study of wire breakup and in-flight particle behavior during wire flame spraying of aluminum", *Journal of*

Thermal Spray Technology, Vol. 26, no. 8, pp. 1947–1958, 2017, DOI: https://doi.org/10.1007/s11666-017-0639-1.

[14] Bhosale, D. G., et al., "High temperature solid particle erosion behaviour of SS 316L and thermal sprayed WC-Cr3C2–Ni coatings", *Wear*, Vol. 462, pp. 203520, 2020. DOI: https://doi.org/10.1016/j.wear.2020.203520.

[15] Liu, W.-H., Shieu, F.-S., and Hsiao, W.-T., "Enhancement of wear and corrosion resistance of iron-based hard coatings deposited by high-velocity oxygen fuel (HVOF) thermal spraying", *Surface and Coatings Technology*, Vol. 249, pp. 24–41, 2014, DOI: https://doi.org/10.1016/j.surfcoat.2014.03.041.

[16] Hardwicke, C. U. and Lau, Y.-C., "Advances in thermal spray coatings for gas turbines and energy generation: a review", *Journal of Thermal Spray Technology*, Vol. 22, no. 5, pp. 564–576, 2013, DOI: https://doi.org/10.1007/s11666-013-9904-0.

[17] Adarsha, H., et al., "Investigations on the abrasive wear behaviour of molybdenum coating on SS304 and A36 using HVOF technique", *Materials Today: Proceedings*, Vol. 5, no. 11, pp. 25667–25676, 2018, DOI: https://doi.org/10.1016/j.matpr.2018.11.008.

[18] Hong, S., et al., "Microstructure and electrochemical properties of nanostructured WC–10Co–4Cr coating prepared by HVOF spraying", *Surface and Coatings Technology*, Vol. 235, pp. 582–588, 2013, DOI: https://doi.org/10.1016/j.surfcoat. 2013.08.029.

[19] Szymański, K., et al., "Thermally sprayed coatings resistant to erosion and corrosion for power plant boilers-A review", *Surface and Coatings Technology*, Vol. 268, pp. 153–164, 2015, DOI: https://doi.org/10.1016/j.surfcoat.2014.10.046.

[20] Patil, V., et al., "High Temperature Corrosion Behavior of High Velocity Oxy Fuel Sprayed NiCrMoFeCoAl-30% SiO2 and NiCrMoFeCoAl-30% Cr2O3 Composite Coatings on ASTM SA213-T22 Steel in a Coal-fired Boiler Environment", *International Journal of Engineering: Transactions A: Basics*, Vol. 35, no. 7, pp. 1416-1427, DOI: https://doi.org/10.5829/ije.2022.35.07a.19.

[21] Kumar, D., Murtaza, Q., and Singh, R., "Sliding wear behavior of aluminum alloy coating prepared by two-wire electric arc spray process", *The International Journal of Advanced Manufacturing Technology*, Vol. 85, no. 1, pp. 237–252, 2016, DOI: https://doi.org/10.1007/s00170-015-7920-6.

[22] Lima, C., et al., "Assessment of abrasive wear of nanostructured WC-Co and Fe-based coatings applied by HP-hVOF, flame, and wire arc spray", *Journal of Thermal Spray Technology*, Vol. 23, no. 7, pp. 1097–1104, 2014, DOI: https://doi.org/10.1007/s11666-014-0101-6.

[23] Kumar, S., Kumar, M., and Handa, A., "Comparative study of high temperature oxidation behavior and mechanical properties of wire arc sprayed NiCr and NiAl coatings", *Engineering failure analysis*, Vol. 106, pp. 104173, 2019, DOI: https://doi.org/10.1007/s11666-014-0101-6.

[24] Yang, Q., Zhao, L., and Patnaik, P., "Erosion performance, corrosion characteristics and hydrophobicity of nanolayered and multilayered metal nitride coatings", *Surface and Coatings Technology*, Vol. 375, pp. 763-772, 2019, DOI: https://doi.org/10.1016/j.surfcoat.2019.07.074.

[25] Kumar, R. and Kumar, S., “Thermal Spray Coating: A Study”, *International Journal Of Engineering Sciences & Research Technology*, Vol. 7, no. 3, pp. 610–617. DOI: https://doi.org/10.5281/zenodo.1207005.

[26] Pattankude, B. G. and Balwan, A., “A Review On Coating Process”, *International Research Journal of Engineering and Technology*, Vol. 6, no. 3, pp. 7980–7984, 2019.

[27] Poursaeidi, E., Torkashvand, K., and Mohammadi, M., “Air Plasma Sprayed Bond Coat Oxidation Behavior and its Resistance to Isothermal and Thermal Shock Loading”, *International Journal Of Engineering. Transactions C: Aspects*, Vol. 32, no. 6, pp. 872–876, 2019, DOI: https://doi.org/10.5829/ije.2019.32.06c.11.

[28] Thiem, P., et al., “Comparison of microstructure and adhesion strength of plasma, flame and high velocity oxy-fuel sprayed coatings from an iron aluminide powder”, *Surface and Coatings Technology*, Vol. 324, pp. 498–508, 2017, DOI: https://doi.org/10.1016/j.surfcoat.2017.06.016.

[29] Goldbaum, D., et al., Review on cold spray process and technology US patents, in *Modern Cold Spray*, *Springer*, pp. 403–429. 2015.

[30] Suo, X., et al., “Preparation and characterization of magnesium coating deposited by cold spraying”, *Journal of Materials Processing Technology*, Vol. 212, no. 1, pp. 100-105, 2012, DOI: https://doi.org/10.1016/j.jmatprotec.2011.08.010.

[31] Rani, S., Agrawal, A. K., and Rastogi, V., “Failure analysis of a first stage IN738 gas turbine blade tip cracking in a thermal power plant”, *Case studies in engineering failure analysis*, Vol. 8, pp. 1–10, 2017, DOI: https://doi.org/10.1016/j.csefa.2016.11.002.

[32] Schiefler Filho, M., et al., “Influence of process parameters on the quality of thermally sprayed X46Cr13 stainless steel coatings”, *Journal of the brazilian society of mechanical sciences and engineering*, Vol. 26, no. 1, pp. 98–106, 2004.

[33] Gong, X., et al., “Microstructure evolution of an EB-PVD NiAl coating and its underlying single crystal superalloy substrate”, *Journal of Alloys and Compounds*, Vol. 672, pp. 36-44, 2016, DOI: https://doi.org/10.1016/j.jallcom.2016.02.115.

[34] Kopec, M., et al., “Aluminide thermal barrier coating for high temperature performance of MAR 247 nickel based superalloy”, *Coatings*, Vol. 11, no. 1, pp. 48, 2021, DOI: https://doi.org/10.3390/coatings11010048.

[35] An, T. F., et al., “Effect of the Al2O3 transformation in scales on the oxidation behavior of a nickel-base superalloy with an aluminide diffusion coating”, *Oxid Met*, Vol. 54, no. 3/4, pp. 301–316, 2000, DOI: https://doi.org/10.1023/A:1004654429687.

[36] Miracle, D., “Overview No. 104 The physical and mechanical properties of NiAl”, *Acta metallurgica et materialia*, Vol. 41, no. 3, pp. 649-684, 1993, DOI: https://doi.org/10.1016/0956-7151(93)90001-9

[37] Hesari, F., Moradi, M., and Torknik, F., “Transmission Electron Microscopy Sample Preparation of INCONEL 738 Nickel-Base Superalloy”, *International Journal of Engineering*, Vol. 32, no. 6, pp. 852–859, 2019, DOI: https://doi.org/10.5829/ije.2019.32.06c.08.