

Failure Evaluation of Thermal Spray Coating Using High-Velocity Oxy-Fuel (HVOF) on Steam Turbine Shaft 940-PT 2 A/B



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ABSTRACT: The repair of worn steel shaft surfaces in power transmission systems is made possible by thermal spray procedures, which have become an essential technology in many sectors. With this novel approach, worn shaft components may be recycled effectively since an API 687-compliant wear-resistant coating designed for specialty rotating equipment repairs is applied. The process's efficacy stems from its capacity to extend the functional life of essential mechanical components, therefore decreasing replacement expenses and downtime. The variety of factors that affect the result highlights the intricacy of thermal spray techniques. Finding the ideal mix of these crucial process variables becomes essential to provide the required degree of wear resistance. The coated shafts perform better as a result of this careful tuning, which also guarantees dependability under challenging working conditions. The coated shafts' surface hardness data in this investigation showed that the initial coating hardness value was below the predetermined goals. Several parts that interact with the shaft were redesigned strategically in response to these discoveries. These adjustments were mainly motivated by economic considerations, to optimize effectiveness while resolving the noted hardness deficiencies. Furthermore, a thorough analysis of failure data showed important correlations between different operational parameters and how they interacted, offering a further understanding of how these factors affected wear resistance. This research allowed for the identification of crucial parameters that required change and emphasized the precise balance essential for optimum thermal spray application. All things considered, this study emphasizes how critical it is to use a methodical approach to improve thermal spray processes, guarantee successful shaft component restoration, and ultimately increase the operational longevity of such components in challenging applications.

Key words: Thermal spray processes, high-velocity oxy-fuel (HVOF), particle velocity, steam turbine shaft, over-clearance

1. INTRODUCTION

An important part of Indonesia's total economy is the energy industry. The energy sector not only provides for the country's energy needs but also makes a substantial contribution to foreign exchange reserves, especially when it comes to the export of oil and gas. Due to factors such as population growth, economic expansion, and fast-paced advancements in the transportation and industrial sectors, Indonesia's energy consumption has been steadily rising over time [1].

PT. XX is dedicated to enhancing and expanding high-quality Fuel Oil products and services to consumers. The company is also committed to strengthening its marketing initiatives, focusing on business-to-business (B2B) operations both domestically and internationally, while consistently providing high-quality products and services.

To sustain its oil processing business, PT. XX operates several oil refineries throughout Indonesia, including Refinery Unit (RU) I in Pangkalan Brandan, RU II in Dumai, RU III in Plaju, RU IV in Cilacap, RU V in Balikpapan, RU VI in Balongan, and RU VII in Kasim [2]. The primary objective of these oil refineries is the

procurement and distribution of Fuel Oil to support national development.

In producing its products, PT. XX—particularly RU II Dumai—utilizes a Steam Turbine Shaft 940-PT 2 A/B in its Fuel Oil processing system. However, during operations, this turbine has experienced dimensional damages and excessive clearance, which has hindered its optimal performance. If any turbine component of the turbine fails, the power facility will perish [3]. This has the potential to cause economic losses if the disruption lasts for an extended period [3].

To restore the Steam Turbine Shaft 940-PT 2 A/B to its proper functioning condition, it is essential to repair the shaft while considering its wear and corrosion resistance. A suitable process for addressing these issues is the thermal spray coating method known as High-Velocity Oxygen-Fuel (HVOF) [4]. High-velocity oxy-fuel (HVOF) coating is a thermal spray thermal spray coating process that is

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used to repair or restore the surface of a component (properties or geometry). This surface engineering technique allows for better equipment life extension by increasing resistance to erosion and wear and protection against corrosion [5]. High-velocity oxygen fuel, or HVOF, spraying, plasma spraying, and flame spraying are examples of thermal spray coating. To drive a powdered feedstock onto the substrate's surface, this technique combines fuel gas and oxygen to generate a high-velocity flame [6-8]. In many applications, HVOF spraying is a very adaptable and powerful method of protecting and improving the performance of a wide range of surfaces. In one recent study, Singh et al. [7] used HVOF spraying to create a CuNi-Cr coating. They found that the coating formed a strong connection and improved the coating's resilience to slurry erosion. Additionally, Bansal et al. [9] used HVOF to build a WC-based coating and saw encouraging outcomes. Meanwhile, coating using the HVOF method and tungsten carbide coating material are the most effective choices for providing friction resistance [10]

2. MATERIALS AND EXPERIMENTAL PROCEDURES

Based on the datasheet obtained from PT. XX, the substrate material used is AISI 4140. The chemical composition of the turbine shaft material is shown in Table 1. In contrast, the operating temperature of the 940-PT 2 A/B steam turbine is usually 371°C to 398°C (max). The coating process of the Steam Turbine Shaft 940-PT 2 A/B follows the API 687 standard so that during the application in the turbine shaft surface coating process, the substrate temperature is maintained below 180°C (350°F) [11]. This condition is maintained to ensure no bending, distortion, or other physical damage during the coating application.

HVOF is a Thermal Spray Coating (TSC) process that takes place under high pressure and combustion temperature conditions. This HVOF process involves heating the powdered feedstock material to form a melt or semi-melt, then feeding it through a spray gun, and then spraying it with a pressurized gas flow on the substrate surface to form a new layer surface structure [5]. The HVOF gun schematic is shown in Figure 1. At the same time, the

HVOF process parameters follow the API 687 thermal spraying process parameters shown in Table 2.

Table 1 Chemical composition of AISI 4140

Element	Content (%)
Cr	0.80-1.10
Mn	0.75-1.0
C	0.380-0.430
Si	0.15-0.30
Mo	0.15-0.25
P	0.035
Fe	Balance

Table 2 Thermal spraying process parameters [11].

	HVOF
Fuel	Various Gases
Particle Velocity (FPS)	1,800–2,600
% Porosity	< 2
Finished Thickness (mils)	7–25
Bond Strength* Per Standard ASTM Test (psi)	12,000
Bond Strength** Per Modified ASTM Test (psi)	16,000
Hardness***—RC	72
Substrate Temperature °F (during application)	350

*ASTM C 633-79 test is limited to about 12,000 psi as epoxy fails; modified test uses brazing.

**Modified ollard test.

***Maximum hardness measured by diamond pyramid method and converted to RC.

Note: Metallizing and plasma spray coatings are shown shaded for information only and are not recommended.

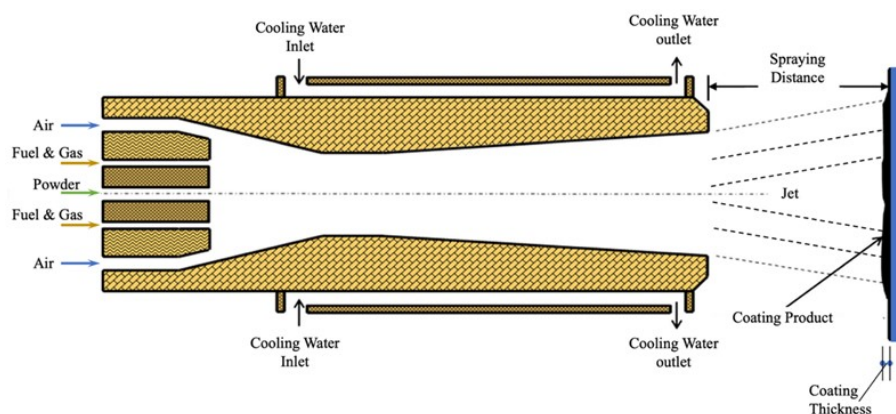


Fig. 1. The Schematic of the HVOF spray gun is adapted from the article by Khan et al. 2019 [12]

The raw material considered for use as a thermal spray coating material is tungsten carbide (WC) powder. Tungsten carbide is a binary compound consisting of equal numbers of tungsten and carbon atoms [13]. Tungsten carbide has a stiffness about twice that of steel, as it has a Young's modulus ranging from about 530 to 700 GPa. The substance's melting point is about 2800°C, and it has a density of 15.63 g/cm³. Tungsten carbide powder is highly sought after for various structural applications due to its extremely high melting point, hardness, and electrical conductivity. Therefore, tungsten carbide can be used in wear-resistant coatings and abrasive materials [13].

The thickness measurement of the coating was carried out using a Digital Point Micrometer IP65 with a digital step of 0.001 mm and an accuracy of 0.002 mm. At the same time, the hardness value of the coating is known to consider the resistance to scratches and wear. This hardness measurement was carried out using a Vickers Hardness Tester (W-5310, Sheffield-UK). The measurement was carried out with five repetitions for each coating, and the average value was reported. To prevent coating delamination, the cutting operation was started from the surface of the coating and not from the substrate.

3. RESULTS AND DISCUSSION

Based on the established procedures of PT. XX, before coating the turbine shaft using HVOF with tungsten carbide coating, Nondestructive testing (NDT) must be carried out on the shaft surface. The NDT test used is the Liquid Penetrant Test, which aims to find defects on the exposed surface of the solid component.

To facilitate understanding of the Steam Turbine Shaft 940-PT 2 A/B, the shaft is marked with two parts: the Drive End (DE) and the Non-Drive End (NDE). Drive End (DE) and Non-Drive End (NDE) refer to the location/position of

the drive (Drive) so that DE is the position closest to the drive while NDE is at the end of the furthest position from the drive, as shown in Figure 2.

Based on the evaluation of the shaft carried out through Nondestructive testing, small cracks were found in the DE section, while no cracks were found in the NDE section. The next step is to feed the shaft diameter (undercutting) to eliminate cracks while considering the thickness of the HVOF layer. To determine the target thickness of the tungsten carbide layer on the DE and NDE bearing journal area shafts, the average diameter data is reduced by the actual diameter data after the final diameter feed (undercutting) is carried out to restore the shaft diameter.

Based on the calculations carried out, the target value of the tungsten carbide layer thickness on both sides of the DE and NDE shafts ranges from: (0.495 mm ~ 0.497 mm). This value still meets the coating standards in API 687 with a range of values (0.178 mm ~ 0.635 mm), then tungsten carbide coating with the HVOF technique can be carried out. The appearance of the installed turbine shaft and the results of the tungsten carbide coating with the HVOF technique on the DE and NDE shaft sides are shown in Figure 3.

Coating hardness is important for applications that consider wear resistance. Hardness testing with the Rockwell method is used to determine the hardness of the material coating. Hardness testing is carried out on both sides of the DE and NDE shafts before and after coating. This aims to determine the increase in hardness value on the surface of the shaft material coating. The results of measuring the average hardness value on the DE shaft side before the coating was obtained at 20 ± 2.83 HRC, and after coating, was obtained at 49 ± 5.66 HRC. At the same time, the average hardness value on the NDE shaft side before the

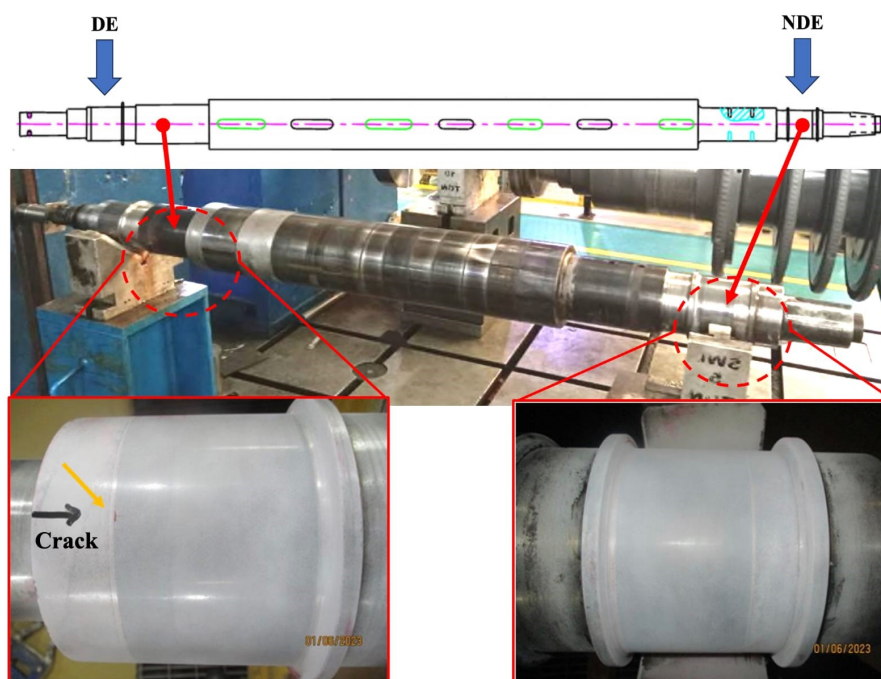


Fig. 2. Nondestructive testing on the DE and NDE shaft sections

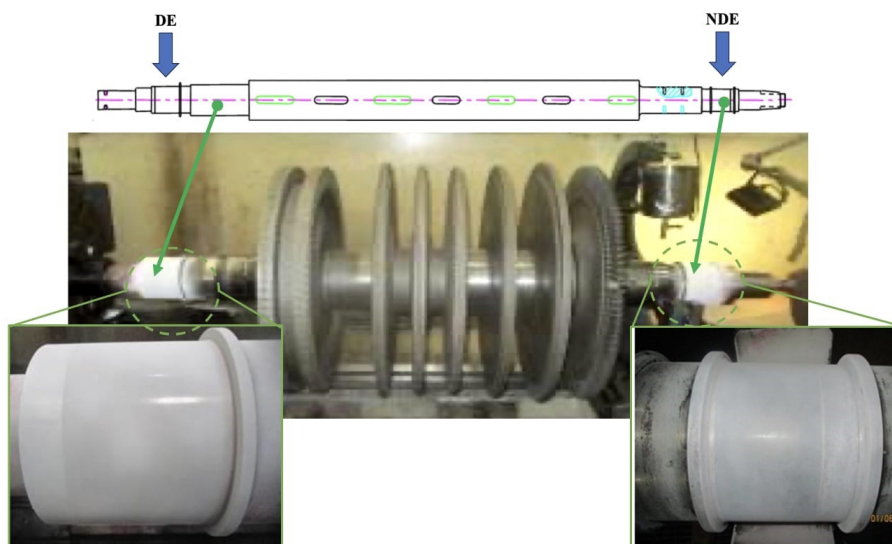


Fig. 3. Turbine shaft following coating

Table 3 Test results for hardness both before and after coating

Position	SHAFT DE	SHAFT NDE	SHAFT DE	SHAFT NDE
TESTING	Before coating	Before coating	After coating	After coating
HARDNESS (HRC)	18~22	18~22	47.5~50.7	46.6~52.8
COATING MAT'L	AISI 4140	AISI 4140	TUNGSTEN CAR-BIDE	TUNGSTEN CAR-BIDE
THICKNESS (μm /	NO	NO	388~396	286~290

After observation based on the test result table (Table 3) where the maximum hardness value on both sides of the DE and NDE shafts did not reach the maximum target required by API 687, then the hardness value required by API 687 is 72 HRC [11], which is the standard used by PT. XX. Considering the importance of the 940-PT 2 A/B Steam Turbine Shaft, it is attempted to keep it operating and the coated shaft can be used. Therefore, other alternatives are sought by considering other components that are in contact with or directly related to the shaft. If observed, the component that comes into contact with the steam turbine shaft is the bearing.

Based on the datasheet obtained from PT. XX journal bearing, as shown in Figure 5, is the normal dimension of the journal bearing used. The hardness value of the bearing made of babbitt material ranges between 23 to 29 HB. Meanwhile, according to Leszczyńska-Madej, B., & Madej, M for the mechanical properties of bearings made of babbitt on steam turbine sliding bearings, the hardness value is 29 HB [14] where this value is much lower than the hardness value of the coated turbine shaft. The operational alternative is to sacrifice bearings so that steam turbine operations can work while considering reducing the maintenance costs of the turbine shaft, which are pretty large.

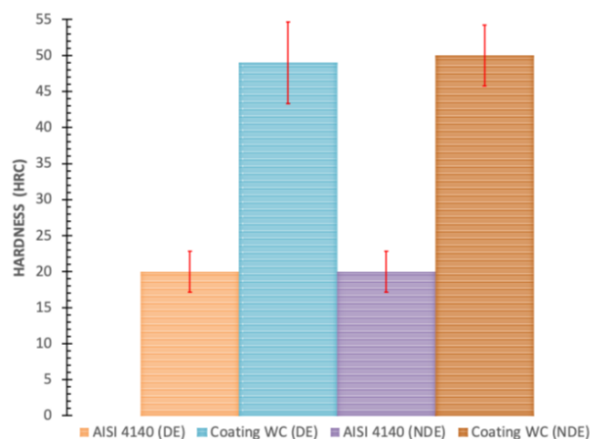


Fig. 4. Hardness values of shaft material before and after coating

By considering the typical dimensions of the DE and NDE bearing journals, it is essential to determine the shaft's clearance outside diameter (OD) of the shaft to the inner diameter (ID). The results of the calculation of the actual clearance between the shaft and the bearing on the DE side obtained a value of 0.211 mm, while the actual clearance between the shaft and the bearing on the NDE side obtained a value of 0.180 mm. Meanwhile, based on the datasheet

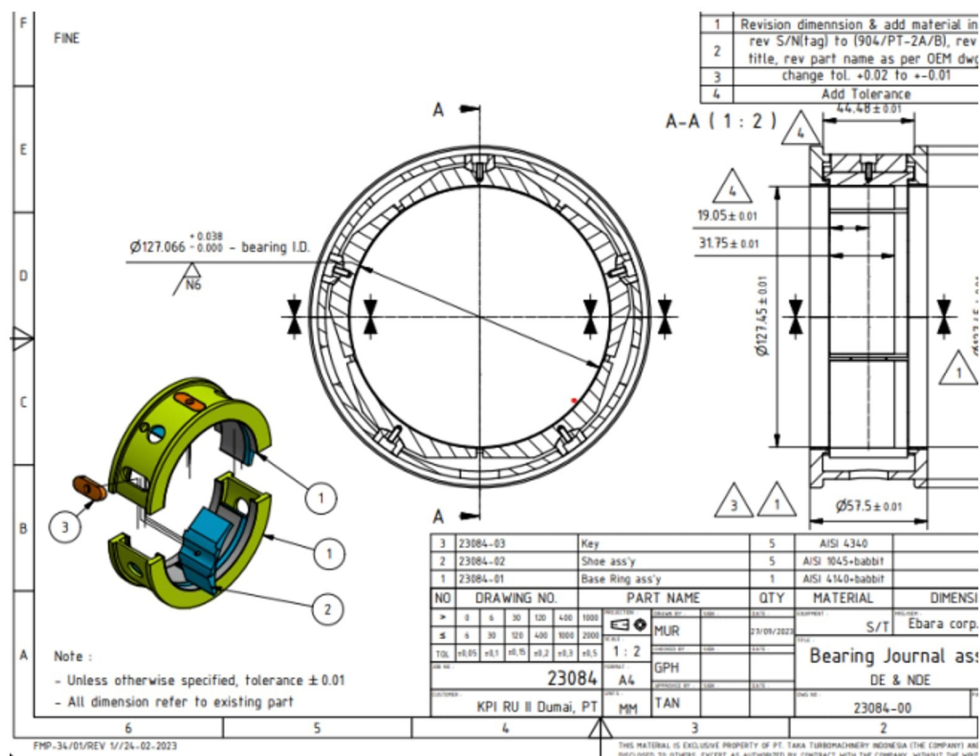


Fig. 5. The Steam Turbine Shaft 940-PT 2 A/B bearing journal's typical dimensions

received from PT. XX, where the clearance for journal bearings, commonly called the clearance of the bearing journal, has a value of 0.127 ~ 0.178 mm. So, from the results above, there is an over-clearance, which can cause other failures on the shaft. After cross-checking and discussing with the turbine operator, this slackness gives an unbalanced effect on the shaft and causes abnormal vibrations.

thing was done by Nur Rohman et al. in analyzing the failure of the condenser tube in a steam power plant [15].

Based on the evaluation results, a matrix was created for several causes that could fail to achieve coating results on the steam turbine shaft, as shown in Table 4.

Table 4. Causes of Thermal Spray Coating Failure Problems on Turbine Shaft

NO.	Cause of Problem	Confirmation Step	Results
1	Particle Velocity (FPS)	No particle velocity measurements were performed during the coating process	Cause
2	% Porosity	No measurements were taken	Cause
3	Substrate temperature	No substrate temperature measurements were performed during the coating process	Cause
4	Substrate history of thermal spray coating applications	Tungsten carbide coating on shafts using the HVOF technique has previously been carried out	Suspicion

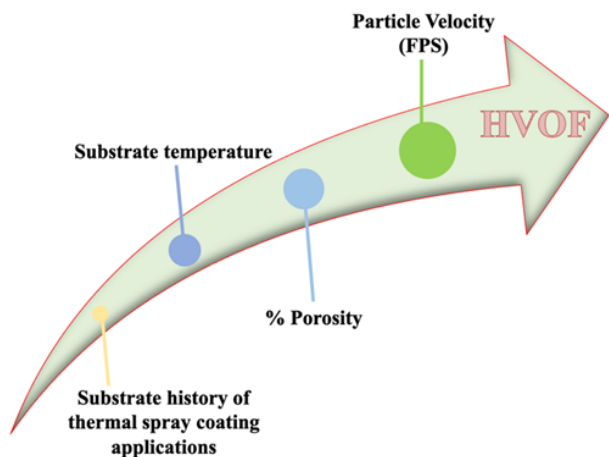


Fig. 6. Fishbone diagram of the steam turbine shaft 940-PT 2 A/B failure evaluation

Based on the data obtained, a comprehensive evaluation of the causes of thermal spray coating failure using high-velocity oxy-fuel (HVOF) on the Steam Turbine Shaft 940-PT 2 A/B was carried out by referring to the thermal spray coating process parameters based on API 687 used by PT. XX and then poured into a fishbone diagram to determine the root of the problem that occurred. The same

The failure matrix of the coating results on the steam turbine shaft above indicates that there are at least three potential causes of issues that could prevent the hardness value from being achieved during the coating process: measuring and testing the porosity of the coating results, not measuring and following the API 867 standard when measuring particle velocity (FPS), and not controlling the substrate temperature during the coating process by the API 867 standard. Meanwhile, Palanisamy et al. [16] said in their research that there is a correlation between porosity and microhardness in the HVOF layer. In another study, Kawakita et al. [17] said that porosity depends on the thickness of the layer and the structure of the layer structure. This is the same as what was conveyed by Houdková et al. [18] where if the material is exposed to high temperatures during use, the coating will experience modifications to its microstructure, which causes possible changes in related properties.

4. CONCLUSION

Based on the evaluation of the failure of Thermal Spray Coating using High-Velocity Oxy-Fuel (HVOF) on the 940-PT 2 A/B steam turbine shaft, several conclusions can be drawn; namely, the hardness value of the shaft coating results were not achieved in the measurement and testing of Particle Velocity (FPS), coating porosity and substrate temperature during the coating process were not documented. The implementation of the coating should follow the procedures or standards that are used as references. In addition, over-clearance is a consideration in the inspection during installation so as not to cause an unbalanced effect that leads to abnormal vibrations.

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REFERENCES

- [1] A. Sa'adah, A. Fauzi, and B. Juanda, "Peramalan Penyediaan dan Konsumsi Bahan Bakar Minyak Indonesia dengan Model Sistem Dinamik," *Jurnal Ekonomi dan Pembangunan Indonesia*, vol. 17, p. 118, 01/01 2017, doi: 10.21002/jepi.v17i2.661.
- [2] PERTAMINA. "Downstream." PT Pertamina (Persero).<https://pertamina.com/id/downstream> (accessed 24 June 2024, 2024).
- [3] P. Anggit Aji, Sunaryo, and N. Ahmad Kafrawi, "Failure Analysis of High-Pressure Turbine Blades in Steam Power Plants," *Journal of Applied Materials and Technology*, vol. 4, no. 1, pp. 24-33, 2022, doi: <https://doi.org/10.31258/Jamt.4.1.24-33>.
- [4] M. Yang, P. Song, D. Kong, T. Huang, and Q. Jin, "Wear and corrosion properties of HVOF sprayed WC-Cr₃C₂ composite coating for application in polysilicon cyclone separator," *Journal of Materials Research and Technology*, vol. 29, pp. 78-89, 2024/03/01/ 2024, doi: <https://doi.org/10.1016/j.jmrt.2024.01.114>.
- [5] TWI. "Technical Knowledge: What Is A High Velocity Oxygen Fuel (HVOF) Coating?" TWI. <https://www.twi-global.com/technical-knowledge/faqs/what-is-a-high-velocity-oxygen-fuel-coating> (accessed 24 June 2024, 2024).
- [6] V. Singh et al., "Cavitation erosion behavior of high velocity oxy fuel (HVOF) sprayed (VC + CuNi-Cr) based novel coatings on SS316 steel," *Surface and Coatings Technology*, vol. 432, p. 128052, 2022/02/25/ 2022, doi: <https://doi.org/10.1016/j.surfcoat.2021.128052>.
- [7] V. Singh, A. K. Singla, and A. Bansal, "Impact of HVOF sprayed Vanadium Carbide (VC) based novel coatings on slurry erosion behaviour of hydro-machinery SS316 steel," *Tribology International*, vol. 176, p. 107874, 2022/12/01/ 2022, doi: <https://doi.org/10.1016/j.triboint.2022.107874>.
- [8] V. Singh, A. Bansal, and A. K. Singla, "Slurry erosion behaviour of HVOF sprayed VC+TiC based novel coatings: Characterization and optimization studies," *Tribology International*, vol. 180, p. 108289, 2023/02/01/ 2023, doi: <https://doi.org/10.1016/j.triboint.2023.108289>.
- [9] A. Bansal, J. Singh, and H. Singh, "Slurry Erosion Behavior of HVOF-Sprayed WC-10Co-4Cr Coated SS 316 Steel with and Without PTFE Modification," *Journal of Thermal Spray Technology*, vol. 28, no. 7, pp. 1448-1465, 2019/10/01 2019, doi: 10.1007/s11666-019-00903-y.
- [10] M. T. Virginie and A. D. Fretes, "Analisis Komparatif Pengaruh Pelapisan HVOF 86WC-10Co-4Cr dan 73WC-20Cr-7Ni Terhadap Ketahanan Abrasi Baja ASTM CA6NM Pada PLTM Karai 7," *Cylinder: Jurnal Ilmiah Teknik Mesin*, vol. 9, no. 2, pp. 1-10, 2023, doi: 10.25170/cylinder.v9i2.4494.
- [11] Rotor Repair, API687, Washington D.C., 2001.
- [12] M. N. Khan, S. Shah, and T. Shamim, "Investigation of operating parameters on high-velocity oxyfuel thermal spray coating quality for aerospace applications," *The International Journal of Advanced Manufacturing Technology*, vol. 103, no. 5, pp. 2677-2690, 2019/08/01 2019, doi: 10.1007/s00170-019-03696-0.

- [13] AHLATCI. "Tungsten Carbide (WC) Micron Powder." Nanografi Nano Technology. <https://nanografi.com/microparticles/compound-micron-powder/tungsten-carbide-wc-micron-powder/> (accessed 1 July 2024, 2024).
- [14] B. Leszczyńska-Madej and M. Madej, "The Properties of Babbitt Bushes in Steam Turbine Sliding Bearings," Archives of Metallurgy and Materials, no. No 3 September, 2011 2011, doi: 10.2478/v10172-011-0089-6.
- [15] A. Nur Rohman, N. Ahmad Kafrawi, and A. Ridwan, "Failure Analysis of Condenser Tube in Unit 1 of the Tenayan Steam Power Plant 2 X 110 MW," in Proceedings of the International Conference of CELSciTech 2019 - Science and Technology track (ICCELST-ST 2019), 2019/12 2019: Atlantis Press, pp. 65-69, doi: 10.2991/iccelst-st-19.2019.13. [Online]. Available: 10.2991/iccelst-st-19.2019.13
- [16] K. Palanisamy, S. Gangolu, and J. Mangalam Antony, "Effects of HVOF spray parameters on porosity and hardness of 316L SS coated Mg AZ80 alloy," Surface and Coatings Technology, vol. 448, p. 128898, 2022/10/25/ 2022, doi: <https://doi.org/10.1016/j.surfcoat.2022.128898>.
- [17] J. Kawakita, S. Kuroda, and T. Kodama, "Evaluation of through-porosity of HVOF sprayed coating," Surface and Coatings Technology, vol. 166, no. 1, pp. 17-23, 2003/03/03/ 2003, doi: [https://doi.org/10.1016/S0257-8972\(02\)00719-3](https://doi.org/10.1016/S0257-8972(02)00719-3).
- [18] S. a. r. Houdková, M. Prantnerová, M. Bystriansky, and F. e. Lukáč, "Thermally Sprayed HVOF Coatings For Steam Turbine Applications," in 7th International Conference Integrity-Reliability-Failure, Portugal, J. F. S. Gomes and S. A. Meguid, Eds., 2020, vol. 7: INEGI-Instituto de Ciência e Inovação em Engenharia Mecânica e Gestão Industrial, pp. 383-392.



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