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Fatigue Behaviour of High-Velocity Oxy-Fuel (HVOF) Coated Steel by Finite Element Analysis

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Abstract: High-velocity oxy-fuel (HVOF) spraying is extensively used in a range of industries. This is because it can reduce component wear, erosion, and corrosion. If mechanical qualities and fatigue behaviour are considered, the impact of the HVOF thermal spraying coating on the components can be contested. The major goals of this work are to investigate the fatigue properties of carbon steel coated with tungsten carbide-nickel and to use finite element analysis to investigate the fracture process of carbon steel coated with tungsten carbide-nickel. The fatigue test for these studies was conducted in ANSYS Workbench software, where the mean theory is set as Goodman theory. Specimens are modelled in SolidWorks software in a dog-bone shape. The fatigue test simulations are run with the 9 kN, 10.5 kN, 12 kN and 13.5 kN forces applied to one of the specimens' ends and fixed support applied to the other. Based on the result, the coated specimens can sustain longer compared to uncoated specimens, and the higher forces will reduce the lifespan of the specimen. The results also show that uncoated specimens receive more damage at maximum compared to coated specimens, and the higher forces will make the damage received by the specimen higher. For fatigue strength, the uncoated specimens have higher stress compared to coated specimens, and the higher forces will make the fatigue strength of the specimen higher. The result for the fracture shows that uncoated steel has the largest smooth region compared to coated steel.

Keywords: Carbon steel, coating, fatigue, thermal spray, finite element analysis

1. Introduction

Carbon steel is a form of steel that is made up of a combination of iron and carbon. It has a higher carbon content, a lower melting point, and is more durable than stainless steel. Carbon steel's disadvantage is that it is difficult to twist and bend into a variety of shapes, which limits its use in some applications. When compared to other steel varieties, carbon steel contains no chromium, making it more susceptible to rust and corrosion. When exposed to dampness for an extended period, it will rust. The coating is used to protect the carbon steel's surface as well as to prevent rust. Surface coating is a low-cost approach to imparting desirable surface properties to materials, tools, and machine components, such as corrosion, erosion, and wear resistance [1]. The thermal spray was used in the coating process, which was conducted in a non-metallic environment.

Thermal spray coating is a process for altering surface properties such as abrasion and corrosion resistance by spraying various materials, either metallic or non-metallic, on a prepared substrate [2]. Thermal spraying is a method of applying thick coatings to a wide range of surfaces. A thermal barrier, as well as appealing and wearable materials, were among the examples [3]. Plasma spraying, high-velocity oxygen fuel spraying, detonation gun spraying, laser-assisted spraying, flame spraying, and electric arc spraying are thermal spray techniques, but this research focuses on HVOF.

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The high-velocity oxy-fuel (HVOF) thermal spray approach has demonstrated significant benefits. This is because of the versatility, robustness, and low cost of producing WC-oriented layers using laser cladding, electrical deposition, and chemical or physical vapour deposition [4]. Low porosity, oxide, and substrate adhesion are all advantages of the HVOF thermal spraying technology. Due to the fast particle speed and low part temperature during the deposition process, HVOF was employed to deposit high-density, superior bond strengths, and low decarburization composite coatings.

Because of its multiple favourable catalytic properties in the hydrogen oxidation and hydrogenolysis reactions, tungsten carbide (WC) has sparked a lot of interest as a potential platinum catalyst substitute [5]. WC was strengthened with binders like cobalt (Co) and nickel (Ni) to improve wear and corrosion resistance [6]. To ensure a high WC material density, these composites were made by pressing a mixture of WC and Fe powders and then melting Ni in a quantity less than the volume of the preform's porosity [7]. Nickel-based alloys have a wide range of applications, including high temperatures, wear, corrosion, impact, and fatigue [8].

Fatigue analysis is a structural analysis of a system's failure tendency under cyclical loads. ANSYS and Abaqus are two examples of software that may be used to evaluate fatigue behaviour under cyclic loads. When a material is subjected to cyclic loading, fatigue causes progressive and localised structural degradation. Continual cycling of high-stress concentrations may eventually result in a crack that spreads and leaks. Fatigue is the term for this type of failure. Damage done during the fatigue process builds up over time and is usually irreversible [9], [10].

Previous research has demonstrated fatigue properties, and most researchers came to the same conclusion, claiming that HVOF coating lowered the fatigue strength of the substrates after utilising a fatigue machine in the lab to conduct fatigue tests [11]. Due to the lack of studies that use simulation to obtain data on the fatigue behaviour of specimens that have been coated, this study will be conducted by finite element analysis, that is, using ANSYS Workbench software to produce fatigue behaviour data. The primary goals of this research are to investigate the fatigue properties of carbon steel coated with tungsten carbide-nickel and the fracture process of carbon steel coated with tungsten carbide-nickel using finite element analysis.

2. Materials and Methods

For this research, the material used for the analysis of the specimen model is carbon steel, while the material coating is tungsten carbide-nickel. The parameters are shown in Table 1 below [12].

Table 1 - The material's properties used in the analysis

Parameter	Carbon steel	WC-Ni	Unit
Density	7850	14500	$kg.m^{-3}$
Yield Strength	250	330	MPa
Tensile Strength	460	370	MPa

Create the required connections between parts to generate the required system or mechanisms and specify the required boundary conditions, such as loads and supports, after acquiring the mesh structure in ANSYS Mechanical. In this study, the load on the left side was set to 9 kN, 10.5 kN, 12 kN and 13.5 kN, while the right side was set to fix support. This study used a fully reversed loading type and applied a load, followed by an equal and opposite load, resulting in a load ratio of R = -1. Various empirical relationships exist, including the Goodman, Soderberg, and Gerber theories, which explain mean stress using static material parameters (yield strength and tensile strength) and S-N data. In this study, the Goodman theory will be chosen above the mean stress theory for the current analysis.

SolidWorks 2021 was used to create the model of a dog bone specimen. Fracture and fatigue studies are performed in ANSYS 2021 R1 simulations for FEA. The reference for modelling the dog bone specimen in unit millimetres is shown in Fig. 1 below. To insert the coating layer, the surface coating's menu in the geometry section can be applied by inserting the material properties of the WC-Ni coating and selecting the coated surface area. The coating thickness of 0.25 mm has been applied at the gauge length of the specimen model.

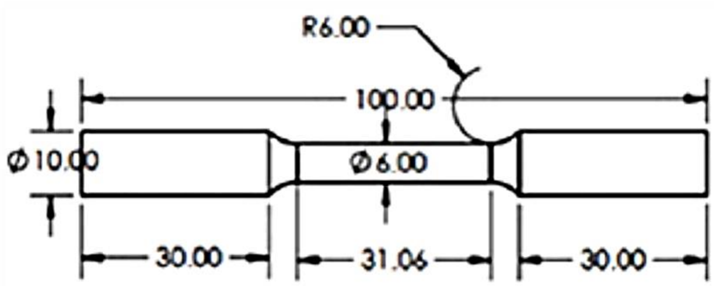


Fig. 1 - Dimension of the specimen

To build the simulation, 7 basic steps must be taken in ANSYS. This strategy can make it easier to run the simulation properly. The ANSYS process flow is shown in the step below. 1) Static Structural Analysis 2) Engineering Data 3) Geometry 4) Model 5) Setup 6) Solution; 7) Results.

Before the solution can be built, the mesh can be built. To do so, right-click your mouse and pick Mesh from the tree outline. Select "Generate Mesh" from the context menu. Keep in mind that if you use the patch independent meshes to produce a mesh and then change the boundary conditions, the meshing will have to be redone, and the time spent meshing will be wasted. Fig. 2 below shows the mesh that was generated for this study. Meshing was important as it represented an element, and the time required to solve depended on these meshing criteria. In this simulation, the mesh on the crack specimen or the notch is finer to gain a more accurate result.

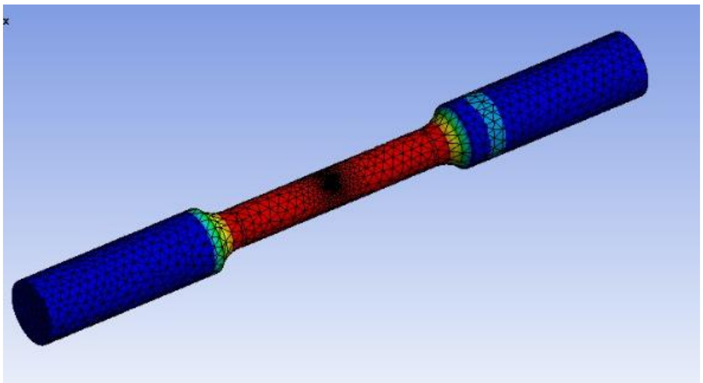


Fig. 2 - Shape of mesh on the specimen

3. Results and Discussion

To obtain data for fatigue test simulations, static structural test simulations were run. To run a fatigue test in ANSYS, a static test is required. The static test data is then used to simulate the fatigue test. These static test simulations were performed by applying forces of 9 kN, 10.5 kN, 12 kN, and 13.5 kN to the right side while leaving the other side as a fixed support. Then, in the fatigue test simulation, a cycle time of 1×10^6 was chosen. This is because any design that exceeds this cycle time is considered long-lasting.

Based on the result, the coated specimens can sustain longer compared to the uncoated specimens for all forces. Fig. 3 shows the bar chart of fatigue life for all forces for uncoated and coated specimens. According to the bar chart, we can see the coated specimen for load 9 kN has the highest value of minimum fatigue life, which is 4925 cycles. Whereas the lowest fatigue life is 1095 cycles, the value for an uncoated specimen for a 13.5 kN load It can be concluded that the higher forces will reduce the lifespan of the specimen, and the coated specimen can last longer than the uncoated specimen. In a previous study, the experimental fatigue strength of the uncoated carbon steel was 317 MPa at 106 cycles, and the fatigue strength of the WC-10 Ni-coated steel was 307 MPa at 106 cycles [11]. In this study, the fatigue life obtained is below the value of 10,000; this happens because of the limitations of the software that reduce the number of cycles. To get accurate values, it is necessary to use the full version of ANSYS software.

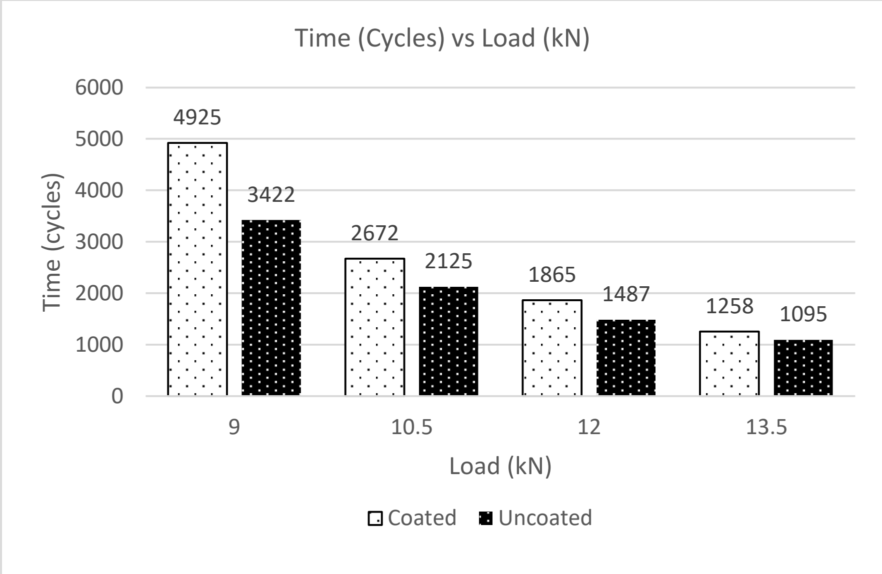


Fig. 3 - Bar chart of fatigue life for all forces for uncoated and coated specimens

The result shows that the uncoated specimens receive more damage at maximum compared to coated specimens for all forces. Fig. 4 shows the bar chart of fatigue damage for all forces for uncoated and coated specimens. According to the bar chart, we can see the uncoated specimen for load 13.5 kN has the highest value of fatigue damage, which is 9.13×10^5 damage. Whereas the lowest maximum fatigue damage is 2.03×10^5 damage, the value for coated specimens at a 9 kN load. It can be concluded that the higher forces will make the damage received by the specimen higher, and the uncoated specimen receives more damage compared to the coated specimen. As a result, because the surface of the coated specimen is harder after being coated with tungsten carbide-nickel, the damage imposed on it is lower [13].

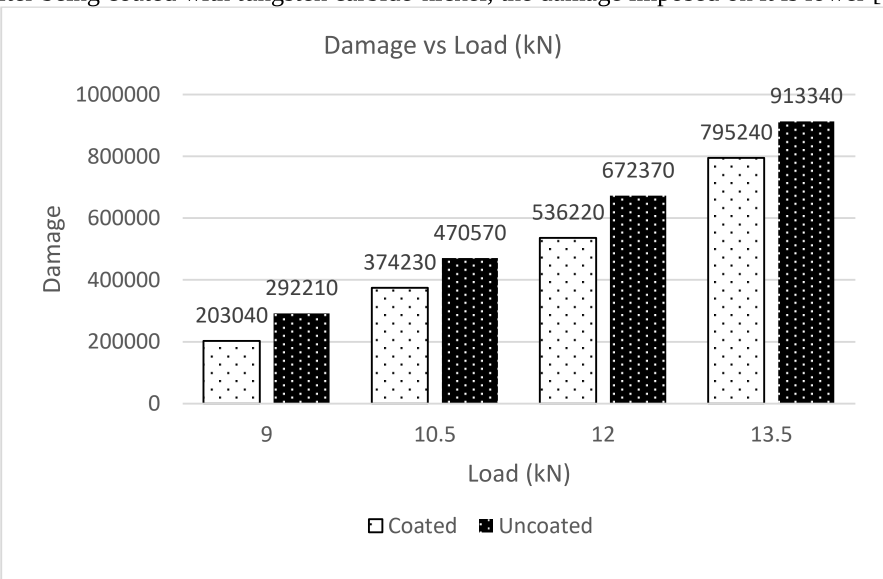


Fig. 4 - Bar chart of fatigue damage for all forces for uncoated and coated specimens

From the result, we can see that the uncoated specimens have higher stress compared to the coated specimens for all forces. Fig. 5 shows the bar chart of fatigue strength for all forces for uncoated and coated specimens. According to the bar chart, we can see that the uncoated specimen for a load of 13.5 kN has the highest value of fatigue strength, which is 555.98 MPa. Whereas for the lowest maximum fatigue strength is 329.47 MPa, the value for coated specimens at 9 kN load. It can be concluded that the higher forces will make the fatigue strength of the specimen higher, and the uncoated specimen receives more stress compared to the coated specimen. The fatigue strength of WC-10Ni-coated steel decreased by 3.2% [14]. In this study, the decrease in fatigue strength for WC-10Ni-coated steel was 5%. The percentage decrease in fatigue strength is different because the size and shape of the mesh used are not the same as in previous studies. The smaller the mesh used, the more accurate the results.

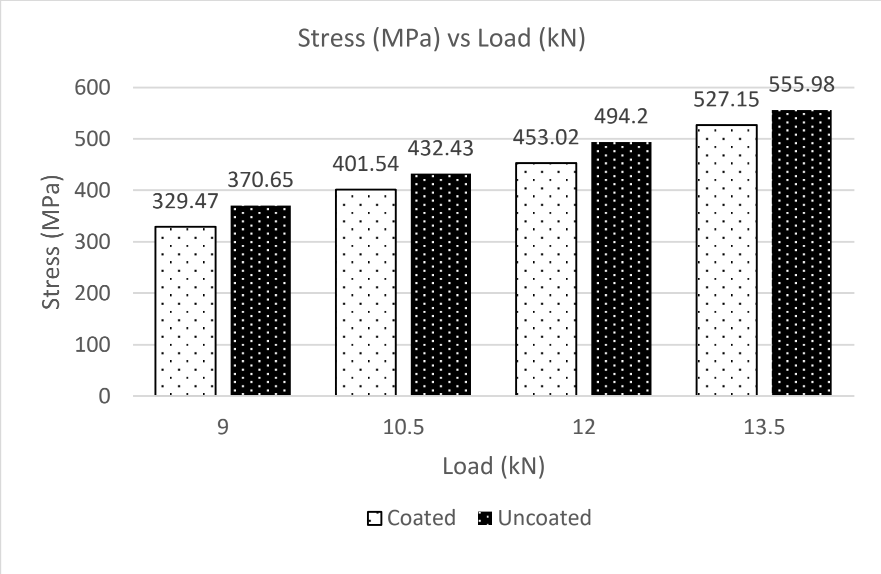
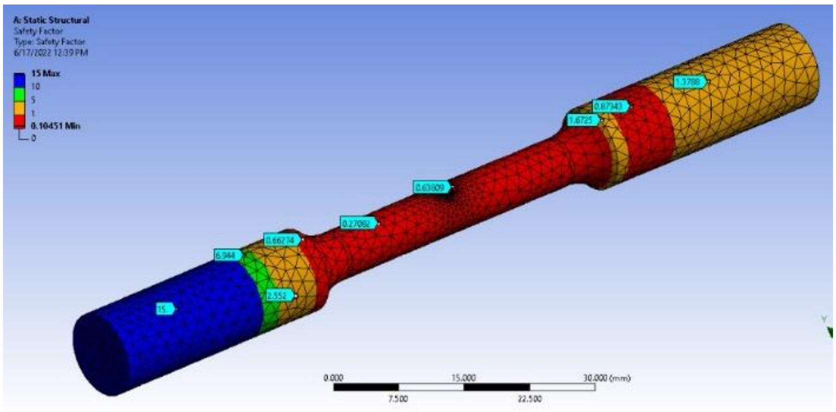
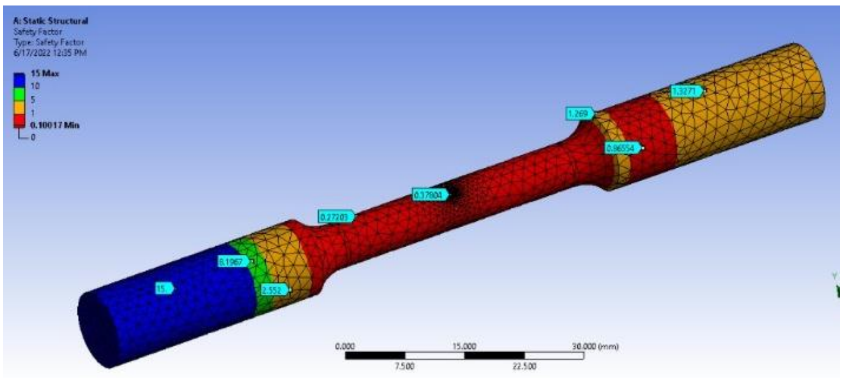


Fig. 5 - Bar chart of fatigue strength for all forces for uncoated and coated specimens

The fatigue safety factor is a safety factor about fatigue failure at a given design life. The maximum safety factor is 15. Values less than one for fatigue safety factors indicate failure before the design life is reached. As a result, neither specimen differs significantly; both represent four colours, with the red colour representing the area of failure, that is, the area with a value less than one. Although the minimum value of each specimen differs by 0.105 for uncoated and 0.100 for coated, it has little effect and only shows areas of failure. Fig. 6 shows the result of the fatigue safety factor for (a) the uncoated specimen and (b) the coated specimen.



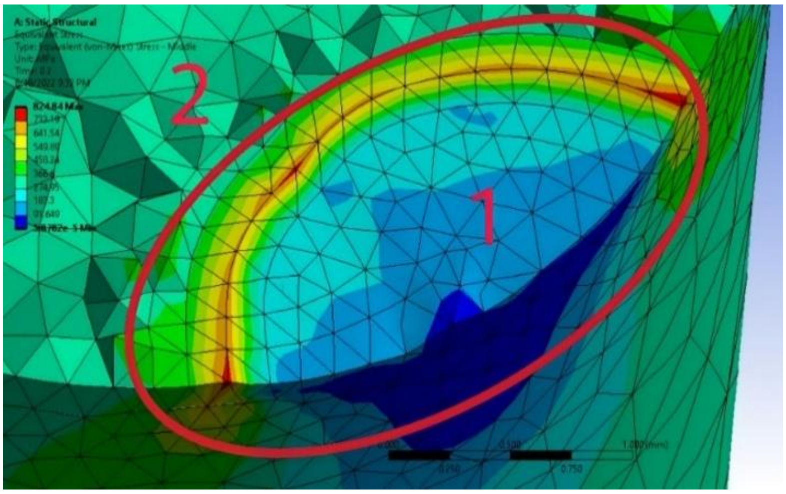
(a)



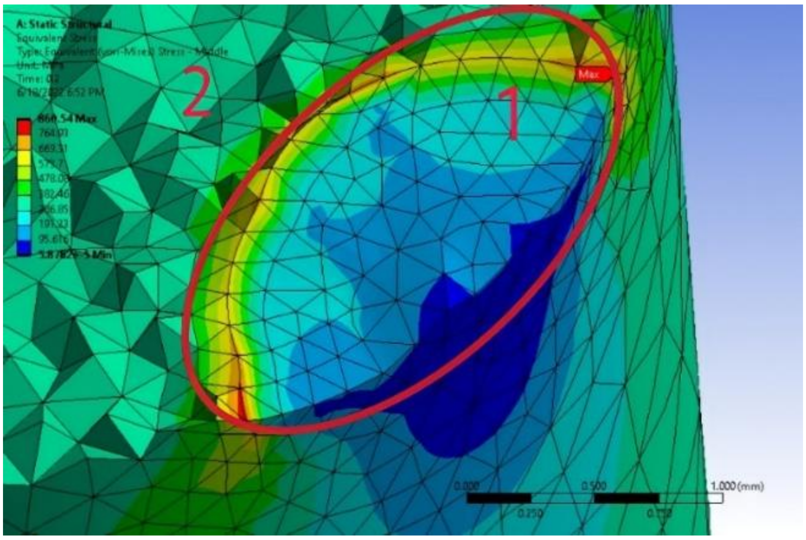
(b)

Fig. 6 - Result of fatigue safety factor for (a) the uncoated specimen and; (b) the coated specimen

Fig. 7 shows two types of specimens: (a) uncoated steel, and (b) WC-10Ni coated steel, both of which were subjected to the same stress amplitude of 9 kN. Both figures are enlarged to a size of 1000 mm to make a comparison. Due to limitations, fracture occurred for only 0.2 s; the specimen had to be cut at the fracture section to see a clearer surface result. In comparison to the WC-12Ni coated steel, the uncoated steel has the largest smooth area. In a fatigue cycle, the final ductile fracture region fractures in a shorter period than the fatigue crack region [15]. As a result, the coated specimen will fracture faster than an uncoated specimen. Because of the faster fracture, the fatigue crack region was smaller, and the final fracture region was larger. The rough region, on the other hand, is where the final ductile fracture occurred. This is due to the notch surface formed by the coated steel because of the coating process, which caused a higher stress concentration and a faster fracture. Stress concentration on the component surface causes cracks close to it to propagate more quickly [16].



(a)



(b)

Fig. 7 - Fracture surface for (a) uncoated steel and; (b) WC-10Ni coated steel

4. Conclusion

The purpose of this paper is to investigate the effect of tungsten carbide nickel high-velocity oxy-fuel coatings on the fatigue behaviour of carbon steel. Based on the result, the coated specimens can sustain longer compared to uncoated specimens, and the higher forces will reduce the lifespan of the specimen. The results also show that uncoated specimens receive more damage at maximum compared to coated specimens, and the higher forces will make the damage received by the specimen higher. For fatigue strength, the uncoated specimens have higher stress compared to coated specimens, and the higher forces will make the fatigue strength of the specimen higher. The result for the fracture shows that uncoated steel has the largest smooth region compared to coated steel. Mesh sensitivity analysis needs to be carried out in the future to consider the role of mesh sizes in terms of stresses.

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References

[1] V. Shibe and V. Chawla, "An overview of research work in hardfacing," *Mech. Confab*, vol. 2, no. 3, pp. 105–110, 2013.

[2] M. S. Lamana, A. G. M. Pukasiewicz, and S. Sampath, "Influence of cobalt content and HVOF deposition process on the cavitation erosion resistance of WC-Co coatings," *Wear*, vol. 398–399, pp. 209–219, Mar. 2018, doi: 10.1016/J.WEAR.2017.12.009.

[3] D. Mohanty, S. Kar, S. Paul, and P. P. Bandyopadhyay, "Carbon nanotube reinforced HVOF sprayed WC-Co coating," *Mater. Des.*, vol. 156, pp. 340–350, Oct. 2018, doi: 10.1016/J.MATDES.2018.06.054.

[4] M. Kutz, *Handbook of environmental degradation of materials*. William Andrew, 2018.

[5] E. Jonda, L. Łatka, and W. Pakieła, "Microstructure and Selected Properties of Cr3C2–NiCr Coatings Obtained by HVOF on Magnesium Alloy Substrates," *Mater. 2020, Vol. 13, Page 2775*, vol. 13, no. 12, p. 2775, Jun. 2020, doi: 10.3390/MA13122775.

[6] E. V. Polyakov, V. N. Krasil'nikov, A. P. Tyutyunnik, N. A. Khlebnikov, and G. P. Shveikin, "Precursor Based Synthesis of Nanosized Tungsten Carbide WC and WC:nCo Nanocomposites," in *Doklady Physical Chemistry*, vol. 457, no. 1, Pleiades Publishing, Ltd., 2014, pp. 104–107. doi: 10.1134/S0012501610090022.

[7] K. Van Acker, D. Vanhoyweghen, R. Persoons, and J. Vangrunderbeek, "Influence of tungsten carbide particle size and distribution on the wear resistance of laser clad WC/Ni coatings," *Wear*, vol. 258, no. 1–4, pp. 194–202, Jan. 2005, doi: 10.1016/J.WEAR.2004.09.041.

[8] C. L. Cramer, A. D. Preston, A. M. Elliott, and R. A. Lowden, "Highly dense, inexpensive composites via melt infiltration of Ni into WC/Fe preforms," *Int. J. Refract. Met. Hard Mater.*, vol. 82, pp. 255–258, Aug. 2019, doi: 10.1016/J.IJRMHM.2019.04.019.

[9] Z. Li, D. Shi, S. Li, and X. Yang, "Residual fatigue life prediction based on a novel damage accumulation model considering loading history," *Fatigue Fract. Eng. Mater. Struct.*, vol. 43, no. 5, pp. 1005–1021, May 2020, doi: 10.1111/FFE.13205.

[10] Muhammad Hilman Karem and Al Emran Ismail, "Finite Element Analysis of Piston for Structural Assessments," *J. Sustain. Manuf. Transp.*, vol. 1, no. 1, pp. 8–16, 2021.

[11] M. A. M. Halmi, M. A. Harimon, A. E. Ismail, and D. Chue, "Fatigue behaviour of high velocity oxy-fuel coatings on medium carbon steel," *Int. J. Eng. Trends Technol.*, vol. 69, no. 6, pp. 56–70, 2021, doi: 10.14445/22315381/IJETT-V69I6P209.

[12] "Tungsten Carbide – Density – Strength – Hardness – Melting Point," 2022. https://material-properties.org/tungsten-carbide-density-strength-hardness-melting-point/

[13] N. Espallargas, J. Berget, J. M. Guilemany, A. V. Benedetti, and P. H. Suegama, "Cr3C2–NiCr and WC–Ni thermal spray coatings as alternatives to hard chromium for erosion–corrosion resistance," *Surf. Coatings Technol.*, vol. 202, no. 8, pp. 1405–1417, Jan. 2008, doi: 10.1016/J.SURFCOAT.2007.06.048.

[14] M. A. Zavareh, A. A. D. M. Sarhan, P. A. Zavareh, B. B. A. Razak, W. J. Basirun, and M. B. C. Ismail, "Development and protection evaluation of two new, advanced ceramic composite thermal spray coatings, Al2O3–40TiO2 and Cr3C2–20NiCr on carbon steel petroleum oil piping," *Ceram. Int.*, vol. 42, no. 4, pp. 5203–5210, Mar. 2016, doi: 10.1016/J.CERAMINT.2015.12.044.

[15] J. Siegl, I. Nedbal, and J. Kunz, "Fatigue crack growth history in damage tolerance design of aircraft structures," *Int. J. Fatigue*, vol. 31, no. 6, pp. 1062–1067, Jun. 2009, doi: 10.1016/J.IJFATIGUE.2008.05.006.

[16] L. O. A. Affonso, *Machinery Failure Analysis Handbook: Sustain Your Operations and Maximize Uptime*. Elsevier Science, 2013. [Online]. Available: https://books.google.com.my/books?id=GRRBAQAAQBAJ