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Comparative Study of the Life Prediction and Failure Analysis of Metal Powder (Vanadium-V) Coated on Crankshaft

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Abstract. The crankshaft plays a crucial role in the efficient operation of internal combustion engines, converting piston reciprocating motion into rotary motion. This study aims at the life prediction and failure analysis of metal powder (Vanadium-V) coated on crankshaft using numerical method. It was modelled with SOLIDWORDS version 2019 and imported to ANSYS 2020 RI environment for static structural analysis. Numerical results of total deformations obtained from ANSYS are shown with the minimum value and maximum for propose material 7.3172e-5 and 0.00065855 respectively, and for the existing material value having 0.00014795 and 0.0013316 as well. Maximum and minimum values are 0.018841 and 2.9158e-7 in crankshaft equivalent elastic strain distributions in the existing material respectively. Results also show that maximum equivalent elastic strain is observed in propose with 0.097538 and minimum 3.1017e-7. The maximum value is 1.3933e9 and minimum value is 26418 of the stress found around the crankshaft of the propose and is stretched where there is concentration of pressure. The maximum stress intensity is observed in existing material with 1.5139e9 with minimum value of 30833. Results reveal significant improvements in total deformations, elastic strain distributions, and stress values for the proposed vanadium-coated material compared to the existing one. Despite a mere 0.0003mm thickness, the vanadium coating offers cost-effectiveness, better performance with cheaper lubricants, reduced friction, and enhanced dimensional tolerance at higher pressures. Results therefore proposed vanadium incorporated to inhibit grain growth to enhance strength and toughness of hardened steel.

Keywords: Crankshaft, carbon steel performance, vanadium coating

Introduction

The crankshaft, responsible for converting piston reciprocating motion into rotary motion, undergoes cyclic loading during its service life, with common failures linked to bending loads during gas combustion. To mitigate future failures, material selection, design, manufacturing, and cost-effective maintenance are crucial, supported by laboratory testing Gu and Zhou (2011). Previous studies have identified stress concentration in critical areas like the crank arm knuckles and main journal, emphasizing the importance of robust design. Utilizing Pro-E, ANSYs, and CATIA-V5, analyses highlighted bending deformations and stress concentrations, particularly at the crankpin's neck surface and fillet areas (Jian et al., 2011). In a static analysis, Thriveni et al. (2016) explored different materials and orientations, validating results against theoretical outcomes. Jaimin and Abhishek (2012) delved into precise stress and deformation understanding for a single-cylinder 4-stroke diesel engine, employing Von-Misses stress, vibration models, and harmonic analysis. Pawam et al. (2016) ensured that designed Von Misses stresses remained below material yield stress in theoretical comparisons. Crankshaft deficiencies, such as bending in various components, often lead to fatigue failure stages, highlighting the critical role of material choice (Jaimin et al., 2012). A study on

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crankshaft modeling and optimization using finite element analysis (Balmurugan, 2011) shows a consistent emphasis on improving performance, reducing weight, and enhancing fatigue strength. The integration of FEA tools like Ansys and ADAMS Farzin and Ali (2007), along with various optimization techniques, demonstrates the multidisciplinary approach in this field Jian (2011). Noteworthy is the attention given to manufacturing processes, material properties, and the impact on crankshaft behavior. In a study conducted by Ramkumar and Krishnaraju (2015), the critical factor influencing engine performance and longevity is strength, particularly in the crankshaft. The extreme forces exerted on the crankshaft with each engine revolution highlight the importance of selecting the optimal material for design. This choice significantly impacts the results achieved and the potential challenges faced. The study explores the comparison between powder metal and forged metal crankshafts, evaluating their respective strengths and performance levels. Additionally, the investigation involves sweeping sine frequencies across the resonance frequency of the crankshaft and measuring the transfer function between the drive signal and the response accelerometer on the fixture. In research by Singh et al. (2019), durability analysis emerges as a fundamental attribute for safe operation, especially in the automotive industry. Emphasizing safety and structural health monitoring, the research aims to quantify the probability of failure under mixed-mode loading. Various protective barriers are implemented to safeguard against system operation hazards. Durability analysis, crucial for product reliability and sustainability assurance, incorporates analytical techniques to understand failure modes and patterns. The accuracy of simulated fatigue life is statistically correlated with actual fatigue through validation using finite element analysis. Taroni (2017) addresses the challenge of satisfying conflicting customer requirements for higher engine performance and better fuel economy in new engines. The study focuses on the prediction of crankshaft durability through the development of a new assessment tool. This tool, based on a comprehensive 3-D mechanical analysis, enhances load calculations, stress calculations, and fatigue prediction. The refined approach allows for quicker and more precise optimization of crankshafts, as demonstrated in the design of a 1.9-liter turbocharged diesel engine crankshaft. Shabana (2015) delves into the selection of steel alloys for high-strength crankshafts. Medium carbon steel alloys, carefully designed to exhibit specific properties, are analyzed for their composition and properties. Alloying elements such as manganese, chromium, molybdenum, nickel, silicon, cobalt, vanadium, aluminum, and titanium contribute distinct characteristics to the material. The study emphasizes the importance of carbon content in determining ultimate strength and hardness, with the alloys commonly used in high-strength crankshafts refined to remove undesirable impurities. In the same study by Shabana (2015) high-strength steels undergo careful refinement to remove impurities like sulfur, phosphorus, and calcium. The highest quality steel is specified in terms of Aerospace Material Specifications (AMS). Vacuum induction melting (VIM) and vacuum arc re-melting (VAR) are highlighted as crucial processes for achieving high-purity steels. The study underscores the importance of specific chemical content and tight controls over the entire manufacturing process for ensuring high-quality crankshaft. Shabana (2015) focuses on the common use of 1038 steel for engine crankshafts. Forged steel crankshafts, known for their low cost and high power, are examined for their suitability in demanding applications. The study emphasizes the importance of preparation work, including stress riser removal and cross-drilling the oil hole, to enhance the performance of forged crankshafts. Various options, such as drilling hollow rod throws and relieving stress through shot peening are discussed, however limited studies are found in the robustness of well-designed forged crankshafts. This study aims at the life prediction and failure analysis of metal powder (Vanadium-V) coated on crankshaft.

Materials and Methods

The crankshaft was modelled using the specifications and conditions (Table 1) with SOLIDWORDS version 2019 as shown in Figure 1; and imported to ANSYS 2020 RI environment for simulation with a meshing size of 2.5 mm (Figure 2) and analysis. Carbon steel (AISI-1026) and Vanadium-V with coated thickness of 0.0003mm were used for the study. Tables 2 and 3 present the mechanical properties of the materials, respectively.

Table 1: Crankshaft specifications and conditions

Parameter	Specification
Crankshaft mass	102 kg
Crankshaft length	1052 mm
Crank radius	72.5 mm
Main journal diameter	100000 mm
Crankpin diameter	7828 mm
Operation	4800 hrs
Engine power	150@2150rpm/kW
Engine torque	785@1500rpm/Nm
Bore diameter	125 mm
Stroke	145 mm
Length of the connection	237 mm
Firing order	1-3-4-2
Reciprocating mass	4.6 kg
Rotating mass	2.6 kg

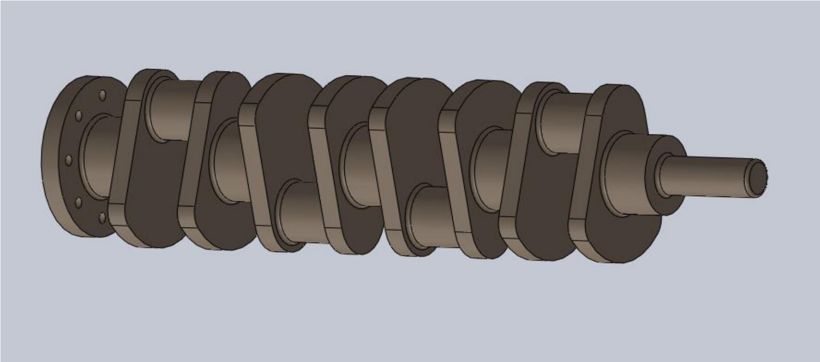

Figure 1. Modelling of crankshaft

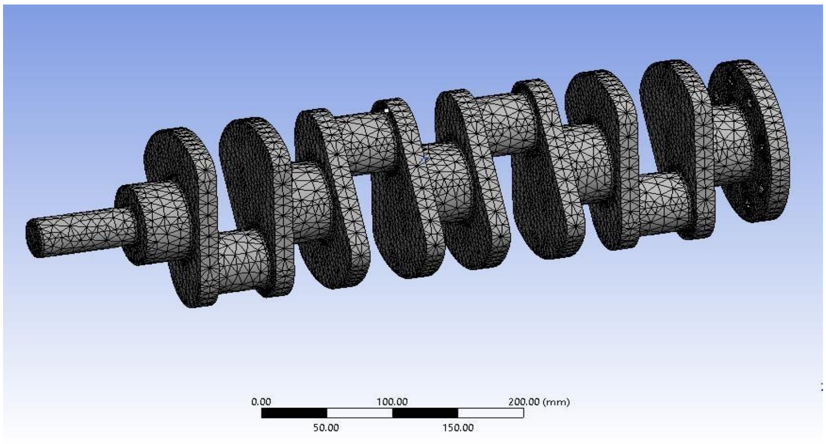

Figure 2. Meshing of the crankshaft

Table 2: Mechanical properties of Carbon steel (AISI-1026)

Properties	**Value**
Density	7858 kg/m^3
Tensile strength	490 MPa
Yield strength	415 MPa
Young modulus	210 GPa
Passion ratio	0.30

Table 3: Mechanical properties of Vanadium-V coated

Properties	**Value**
Density	3350 kg/m^3
Tensile strength	800 MPa
Yield strength	770 MPa
Young modulus	128 GPa
Passion ratio	0.36

Mathematical Model

Thriveni and Chandraiah (2016) calculations for crankshafts Internal Combustion Engines were employed for this mathematical model by this researcher which is governed by the following equations; δ_{BON} = nominal alternating bending stress related to crank pin diameter (N/mm^2) and M_{BON} = alternating bending moment calculated at the outlet of crankpin oil bore (N/mm^2) as in Eqn.(1 and 2)

$$M_{BON} = \pm \tfrac{1}{2} (M_{BOmax} - M_{BOmin}) \quad (1)$$

$$M_{BON} = M_{BTO} \cos \psi + M_{BRO} \sin \psi \quad (2)$$

Where

Ψ = angular position

W_e = section modulus related to cross – section of axially bored crankpin (mm^3)

$$W_e = \pi/32 \left[D^4 - D^4_{BH} \right] / D_o \quad (3)$$

Where

D = crankpin diameter (mm)

D_{BH} = diameter of axial bore in crankpin (mm)

D_0 = diameter of oil bore crankpin (mm)

$$E = D + D_G / 2 \quad (4)$$

Where

E = pin eccentricity (mm)

D_G = journal diameter (mm)

D = crankpin diameter (mm)

* In case of semi- built crankshafts: when T_H □ R_H

Where

R_H = fillet radius of crankpin (mm)

T_H = recess of crankpin (mm)

The web thickness must be considered as Eq. (5) to be equal to

$$W_{ed} = W - (T_H - R_H) \quad (5)$$

-Web Width B must be taken in way of crankpin fillet radius Centre.

Where

W = web thickness (mm)

B = web width (mm)

Results and Discussion

The crankshaft was subjected to structural pressure of 15 MPa and thermal condition of 1000°C for life prediction and failure analysis. Total deformation, equivalent elastic strain and Von Mises stress of the two materials are presented for analysis.

Total Deformation

As depicted in Figure 3, notable deformation is observed around the crankshaft counterweight and pulley end. Following a fundamental mechanical design principle, an excess of counterweight in the crankshaft body typically leads to a decrease in the overall mechanical strength of the design. The structural results of total deformations obtained from ANSYS are shown with the minimum value and maximum for propose material 7.3172e-5 and 0.00065855 respectively, and for the existing material value having 0.00014795 and 0.0013316 as well. The propose material which is vanadium performed better with lesser value than existing material which is carbon steel. The pressure tending to bend the crankshaft is concentrated at the middle but the propose material is resisting the pressure more than the existing.

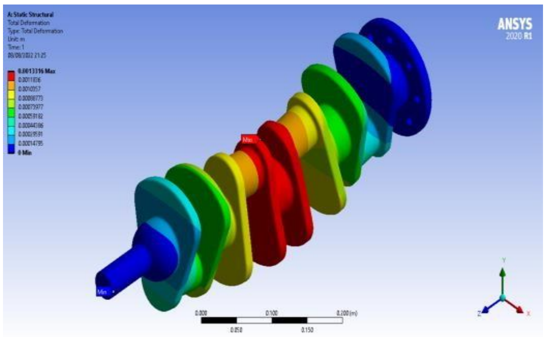

Figure 3(a). Deformation of the Existing

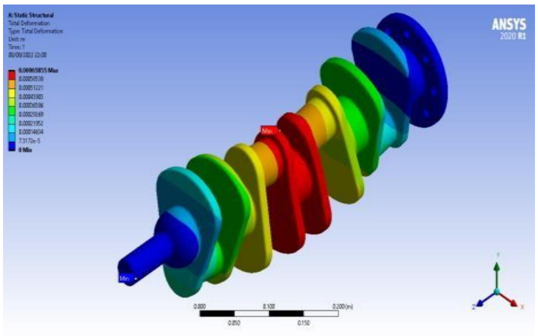

Figure 3(b). Deformation of the Propose

Equivalent Elastic Strain Analysis of the Crankshaft

Figure 4(a) shows the crankshafts elastic strains due to the pressure distribution in the internal combustion engine. Maximum and minimum values of 0.018841 and 2.9158e-7 in crankshaft equivalent elastic strain distributions in the existing material respectively. It also shown in the Figure 4(b) that, maximum equivalent elastic strain is observed in propose with 0.097538 and minimum 3.1017e-7. The high pressure area near the apex of the crankshaft dome had a large expansion, and it gradually decreased away to the crank case. The equivalent strain distributions showed similar distributions among both designs. The maximum equivalent strain value for AISI-1026 were discovered to be 2.9158e-7 respectively for the given loading condition. It was observed that the equivalent elastic strain in both models were more pronounced at the existing crankshaft than the propose, meaning the existing crankshaft is stretching more than the propose material.

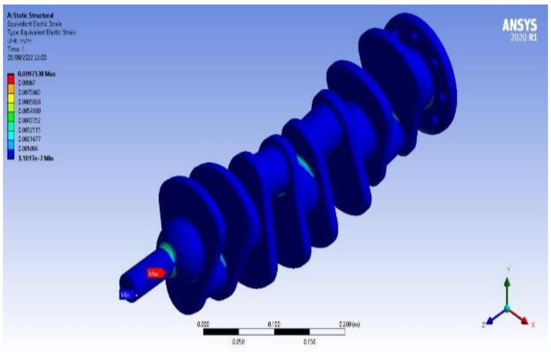

Figure 4(a). Equivalent Elastic Strain for Existing

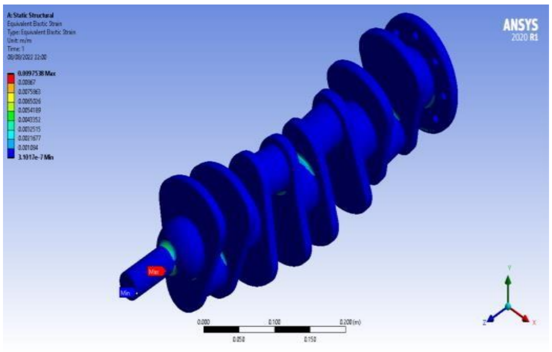

Figure 4(b). Equivalent Elastic Strain for Propose

Stress Distribution

Von-Mises stress distributions are shown in Figure 5(a) and 5(b) along the scaled heat exchanger in cylinder of an engine. The maximum value 1.3933e9 and minimum value is 26418 of the stress found around the crankshaft of the propose and is stretch where there is concentration of pressure as shown in Figure 5(b). The maximum stress intensity is observed in existing material with 1.5139e9 with minimum value of 30833 which is lower than the constraint value which both material satisfied the International Automobile Standard Criteria. It observed that the maximum stress intensity is around the surfaces of bearing in the crankshaft. Whereas the yield strength of the crankshaft is very high in AISI-1026 than Vanadium crankshaft.

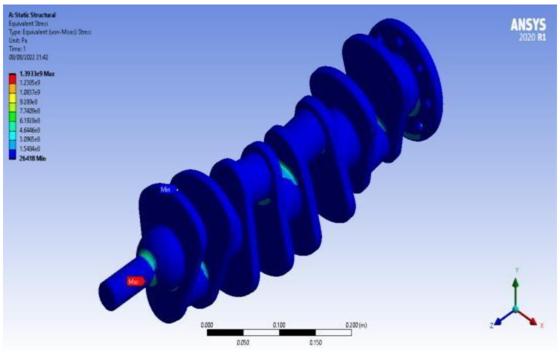

Figure 5(a). Von- Misses Stress Existing

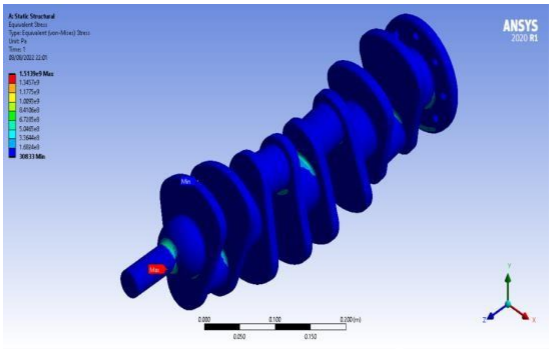

Figure 5(b). Von- Misses Stress Propose

Conclusion

From the study results, vanadium coating shows much encouraging values in equivalent Von Misses stress, strain and deformation as compared to AISI-126 Carbon steel material. Results also show that the carbon steel cycle life is shorter than the vanadium as obtained from the simulation. The vanadium coating is only 0.0003mm thick but advantages derived are cost effectiveness which result in better performance with less expensive lubricant, lesser friction reduction due to low coefficient. It is therefore recommended to manufacturers to use Vanadium-V to enhance strength and toughness of hardened steel.

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