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A Numerical Method to Predict the RCF Behaviour of PVD-coated Transmission Gears and Experimental Results

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Abstract

This work studies the rolling contact fatigue (RCF) behaviour of case-hardened transmission gears for racing motorcycles both numerically and experimentally. Both as-produced and PVD-WC/C coated conditions are analyzed. Finite element models of the gears were developed and a calculation procedure was applied to predict their RCF life. The Ti-6Al-4V alloy was also considered to investigate the mass decrease of the components. RCF tests were carried out in both dry and lubricated conditions. The experimental results were compared with the numerical ones to check the reliability of the predictive method proposed.

Keywords: Rolling contact fatigue; Spur gears; PVD coating; Numerical models; Full-scale tests

1. Introduction

RCF is one of the main sources of damage for transmission spur gears and can be reduced by applying suitable surface hardening treatments [1]. Commonly, case-hardening and nitriding thermal processes are used for improving the surface hardness of steel components, however, in the few years, thin hard coating deposition techniques, such as PVD (Physical Vapour Deposition) and CVD (Chemical Vapour Deposition) have also become of increasing interest from this point of view. In particular, PVD thin hard coatings are used for wear and corrosion behaviour improvement, but recent studies have demonstrated that they can also affect fatigue and (rolling) contact fatigue resistance of the coated components [1-4]. The high values of the compressive residual stresses on the surface and in the initial subsurface layers, induced by the deposition process can, in fact, be effective in reducing RCF crack nucleation and growth [5,6]. As far as the authors know, no significant numerical or experimental studies on the rolling contact fatigue resistance of coated mechanical components, such as spur gears, are available in literature. In this paper, the results of a numerical study on the RCF of PVD-coated and uncoated steel and titanium spur gears [7,8] and of RCF tests on full-scale components are reported. A testing device was designed and assembled to carry out RCF tests under different service conditions. In particular, case-hardened and WC/C-PVD-coated high performance spur gears made of UNI EN-16NiCr11 (AISI 3415) steel were tested under lubricated conditions. The

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tooth surface damage, due to RCF phenomena, was then analyzed.

2. Materials and methods

High performance sixth speed spur gears of a Ducati 1098R racing motorcycle were investigated both numerically and experimentally. The modulus of the pair of gears was 2.5 mm and the tooth thickness was 13 mm. The number of pinion teeth was 25 and the pitch diameter was 64.89 mm, whereas the same parameters for the driven gear were, respectively, 22 and 57.10 mm. The bulk material used for the gears was UNI EN-16NiCr11 (AISI 3415) steel alloy, whereas in the numerical models, the alpha-beta Ti-6Al-4V titanium alloy was also considered [7,8]. The mechanical characteristics of the substrate materials are listed in Table 1. Two different surface treatments were considered both for the experimental and the numerical analyses, namely case-hardening, which is the surface hardening process currently used for the gears, and the 3 μm thick WC/C PVD coating [8]. As reported in Table 2, the hardness profiles of the treatments mentioned are quite different. In particular, the WC/C deposition leads to an extremely high surface hardness compared with the case-hardening one, but the effective depth involved in the surface modification is limited to the coating thickness, whereas the case-hardened layer can be 0.5 mm in depth. The tooth surface roughness measurements, carried out with a Form Taly Surf 50 surface roughness tester, Taylor Hobson, UK, indicated a maximum roughness (R_a) equal to 0.35 μm and 0.08 μm for the case-hardened and WC/C coated surfaces respectively. A Leica MZ75 stereoscopic optical microscope was also used to observe the damaged area of the tested teeth. The measuring axes of the roughness tester are shown in Fig. 1: these axes define the measuring directions of the roughness tester stylus, which is electrically driven along the horizontal direction and is free to translate vertically to follow the tooth profile.

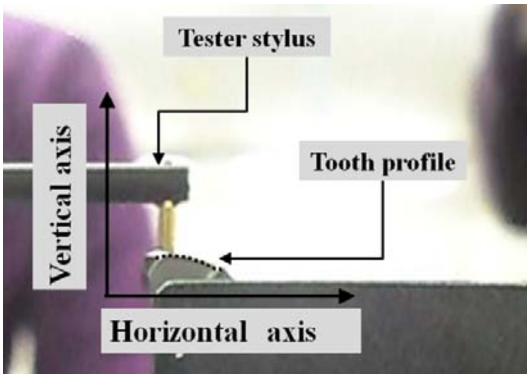

Fig. 1. Example of tooth profile measurement with indication of the measuring axes of the roughness tester.

Table 1. Mechanical properties of the base materials.

Material	16NiCr11	Ti-6Al-4V
Density [kg/m^3]	7800	4500
Young's Modulus [MPa]	206000	113000
Poisson's ratio	0.3	0.34
YS [MPa]	785	880
UTS [MPa]	1030-1280	950

Table 2. Hardness profiles for case-hardening and WC/C-coating.

Treatment	Case-hardening	WC/C-coating
Surface hardness	720 HV	1200 HV
Maximum hardness	760 HV	1206 HV
Core hardness	300 HV	300 HV
Depth of maximum hardness	0.2 mm	0.0015 mm
Effective hardness depth	0.5 mm	0.003 mm

With regard to the FE analyses, due to the gear thickness (13 mm), two-dimensional plain strain models were developed. Both the pinion and the driven gear were completely modelled and a suitable mesh refinement was considered on the teeth involved in the contact. In order to evaluate the whole contact arc, the meshing gears were assembled so that the initial contact condition was close to the outer point of single teeth pair engagement and several rotation steps of about 0.85° each were run. Coupling-kinematic interaction was used to constrain both the meshing gears to their axis of rotation, and pinion rotation was left unconstrained, whereas a suitable rotation opposite to the torque direction was imposed on the driven gear. A torque ranging from 244 Nm to 300 Nm was assumed in the models. Two different analyses were carried out, with the first at 244 Nm, which represents the maximum value of the service torque, was considered as the loading torque, whereas a value 20% higher was assumed in the second since study of the performance of the coating and of the base materials under RCF under overloading conditions was addressed. The sub-modelling technique was used to refine the mesh and improve the accuracy of the results over the contact area. Pre-stress conditions were introduced into suitable solid partitions to reproduce the residual stress field due to the PVD and case-hardening processes. Subsurface initial cracks parallel to the external surface with initial lengths of 5 μm, which is less than the order of the minimum grain size, i.e. 25 μm for the titanium alloy and 65 μm for the steel [9], were simulated. The position and orientation of the subsurface initial defect was assumed so as to comply with possible initial damage due to RCF [7,8]. In order to prevent the crack mating flanks from overlapping during loading, contact gap elements having transversal behaviour with friction coefficients of 0.1 for the steel and 0.3 for the titanium were used. Four-node bilinear plain strain quadrilateral elements (CPE4) were used for the bulk materials and two-node linear two-dimensional truss elements (T2D2) for the coating. A perfectly elastic behaviour for both the coating and the base materials, and the hypothesis of absence of delamination between the coating and the substrate, were assumed. Three-node linear plain strain elements (CPE3) were also used around the crack tip to reproduce the crack tip singularity. Fig. 2a shows the two-dimensional global model developed, with indication of the mesh refinement at the meshing teeth, while in Fig. 2b a detail of the residual stress trend and the initial crack in the submodel are given.

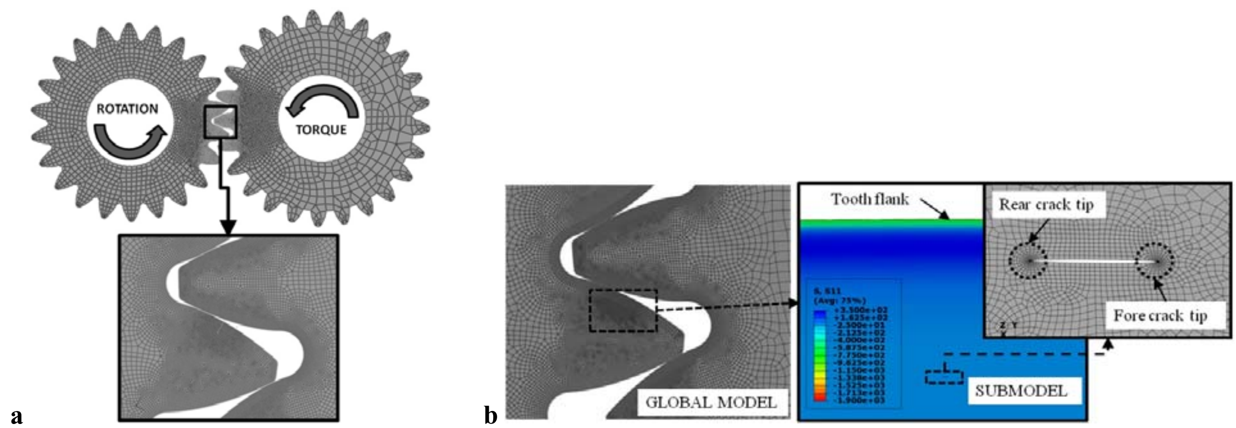

Fig. 2. (a) Two-dimensional FE model of the meshing gears with indication of the loads, constraints and mesh refinement in the contact area and (b) view of the residual stresses and the initial crack in the submodel.

The FE models allowed a discrete simulation of the crack growth due to RCF by applying a theoretical-numerical procedure which requires that the hardness profile, induced by the surface treatment, and the stress intensity factor range at the crack tip for each propagation step are known. According to microstructure fracture mechanics, different models are available for calculation of the threshold stress intensity factor, which is the main parameter for defining the crack propagation [7,8,10-14].

In order to accurately reproduce the rolling contact conditions between the tooth flanks with experimental tests, suitable testing equipment was designed and assembled. The system consisted of a simplified gearbox where only one pair of gears was mounted on two shafts, the drive shaft and the driven shaft respectively. Rotation of the drive shaft was then constrained in order to avoid transmitting the testing torque to the frame. The braking system was designed to prevent transmission of any parasite bending moment or axial force to the shaft. This aspect was particularly important for the reliability of the test results. Parasite bending moments or axial loads could, in fact, overload the teeth in contact, increasing the contact pressure and directly influencing the RCF resistance. The requested testing torque was generated by converting the axial load, given by a universal axial testing machine, into a suitable torque with a specifically designed leverage system. With reference to Fig. 3, the main components of the testing system were the gearbox (1), the support plate (2), the tested pinion (3), the tested driven gear (4), the motor shaft (5), the moving shaft (6), the single row ball bearings (7), the single row cylindrical roller bearings (8), the braking system (9), the leverage system (10) and the loading fork (11). With this device, it was possible to carry out

RCF tests with a torque up to 300 Nm and both dry and lubricated conditions could be simulated. The relative rotation of the meshing gears, that ensured transmission of the load along the whole contact arc, was provided by the torsional stiffness of the shaft. Especially the torsion of the moving shaft, which is longer than the other one, was responsible for the relative rotation of the meshing gears. By changing the axial position of the braking system on the moving shaft, it was possible to regulate the rotation of the meshing gears. To find the initial contact point on the tooth flanks and monitor the test, a suitable video acquisition system was also arranged. A direct measurement of the torque applied was provided at the constrained shaft by means of shear strain gages.

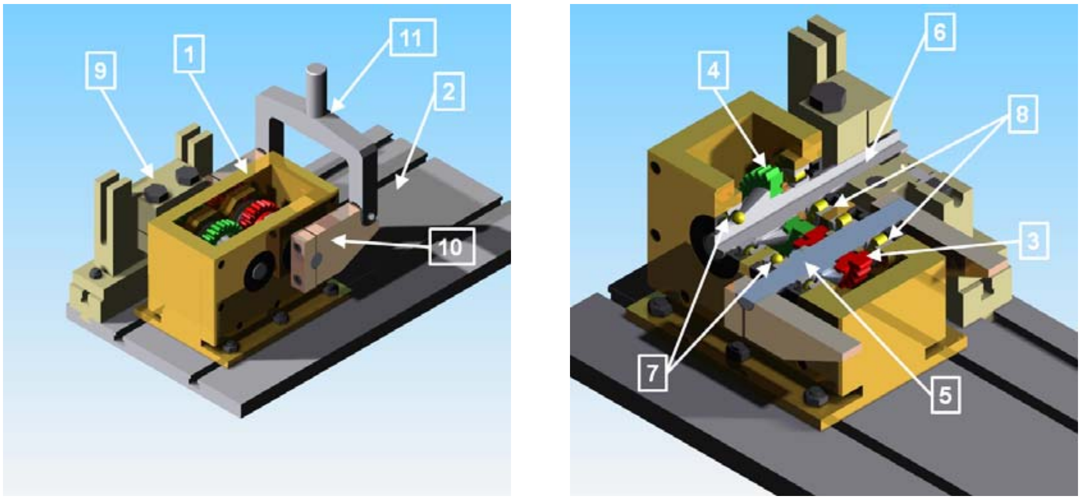

Fig. 3. Scheme of the RCF testing system with indication of the main components.

3. Results and discussion

With regard to the numerical results, case-hardened and WC/C-coated steel and WC/C-coated titanium spur gears were studied. The RCF crack started from an initial depth of 0.15 mm below the external surface where the maximum strains took place, as addressed in previous works, up to the external surface resulting in a spall formation. For the first loading condition considered, i.e. with an applied torque of 244 Nm, no propagation was found for initial cracks shorter than 185 μm and 265 μm for the steel and titanium substrates respectively. During the initial stages, the crack propagated mainly towards the external surface with relative sliding of the flanks (Mode II), with an angle of about 70° with respect to the initial direction, and after that propagation Mode I prevailed. The good behaviour found for the coated titanium gear is probably due to the higher friction coefficient of titanium which had a beneficial effect in reducing the crack propagation Mode II. As a result, the use of titanium as a substrate material could reasonably be taken into account. In the second case, the high torque value applied, i.e. 300 Nm, allowed propagation of 5 μm-long initial cracks, and the maximum stress intensity factor range was higher than the threshold on both crack sides. The total number of cycles up to the subsurface crack which emerged under RCF was also calculated with the theoretical-numerical procedure proposed before and the results showed that the case-hardened steel gears showed the best behaviour against RCF. Nevertheless, the resistance of the coated titanium gears was higher than the coated steel ones (+72 %), highlighting that the titanium option could be considered. The final cracks in the case-hardened and WC/C-coated steel gear and in the WC/C-coated titanium gear teeth are shown in Fig. 4. The numerical results were also confirmed by preliminary experimental RCF tests. The crack shape and the propagation direction found in the investigations on the tested teeth flanks agreed well with the numerical results.

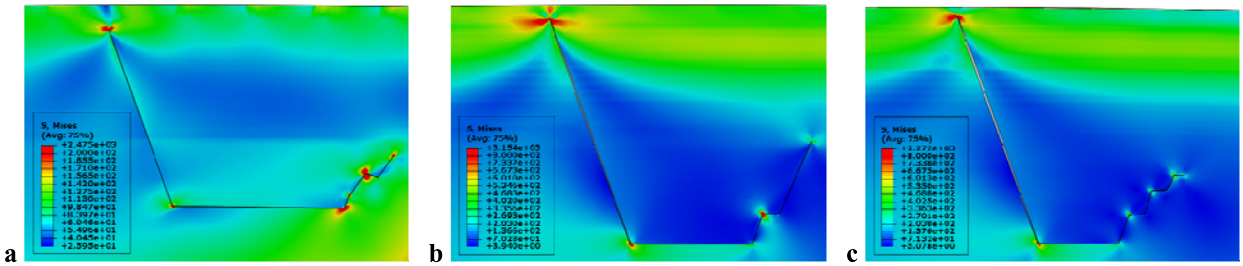

Fig 4. Final cracks due to RCF for (a) steel case-hardened, (b) steel WC/C-coated and (c) titanium WC/C-coated spur gears.

A testing session was carried out by subjecting WC/C-coated and uncoated case-hardened spur gears to 100,000 and 150,000 load cycles under lubricated conditions by means of the RCF testing device outlined above. The tests were performed at a frequency of 1 Hz, by applying the maximum service torque (244 Nm) with a load ratio of 0.1. The lubricant used during the tests was F40 (SAE 15W-50, API SG) racing oil. The tooth flanks subjected to rolling contact fatigue were first optically investigated to qualitatively evaluate the surface state of the damaged area. The tooth damage was also quantitatively investigated both with microscopic observations and roughness and surface profile measurements: for each tooth tested, a cross section of the damaged area and the maximum damage depth, at the middle of the tooth thickness, were evaluated by capturing the tooth flank profile. The measurement results were then processed with a two-dimensional CAD by comparing each damaged profile with an untested one. Examples of measurements of the tooth profile and of the damaged tooth area for a case-hardened uncoated gear after 150,000 load cycles are shown in Figs. 5a and 5b respectively.

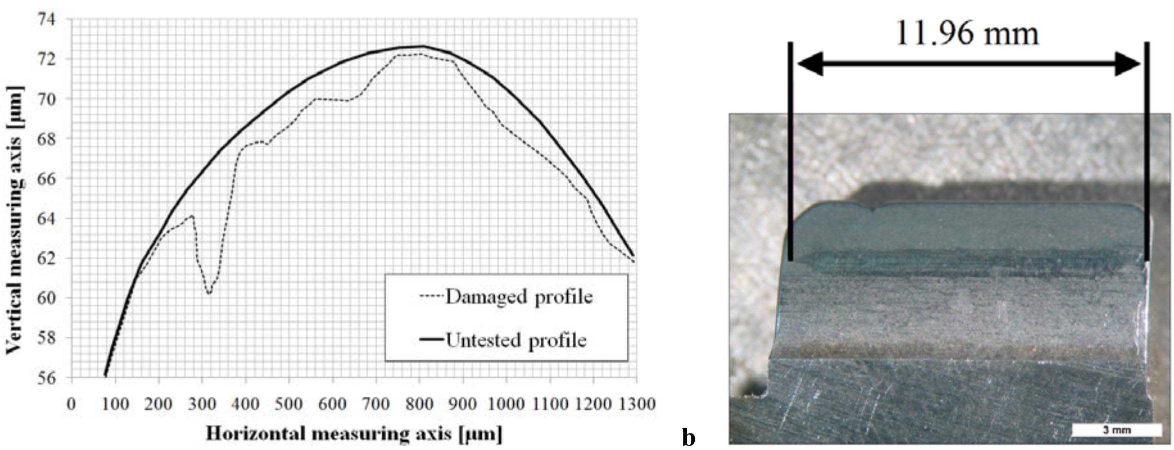

Fig. 5. Examples of measurements of (a) the tooth profile and of (b) the damaged tooth area for a case-hardened uncoated driven gear after 150,000 load cycles.

The results of the tests showed that the cross section areas of the material removed from the tooth surface at the middle of the tooth thickness of the WC/C-coated gears were considerably lower than those of the case-hardened ones after both 100,000 and 150,000 load cycles (Table 3). Therefore, deposition of WC/C could be considered to improve the RCF behaviour of spur gears under lubricated conditions. In fact, preliminary tests carried under dry conditions highlighted that the presence of the lubricant is fundamental to prevent the WC/C film from being damaged or delaminating from the base material.

Table 3. Cross section area of removed material and maximum damage depth at the middle of the tooth thickness for the case-hardened and WC/C-coated gears tested.

	Case-hardened		WC/C-coated	
	100,000 cycles	150,000 cycles	100,000 cycles	150,000 cycles
Cross section of damaged area [µm^2]	1,352	1,561	319	330
Maximum damage depth [µm]	3.0	4.0	1.3	2.0

4. Conclusions

A numerical and experimental study on the RCF behaviour of case-hardened and WC/C-coated high performance spur gears was carried out. A theoretical-numerical procedure was applied to simulate the crack growth from an initial subsurface defect by also considering the residual stress trend induced by the coating deposition and case-hardening process. The possibility of using coated titanium alloys for substitution of standard construction steels was addressed. Experimental tests were carried out under lubricated conditions by means of a custom-made testing device. The numerical findings indicated that titanium alloys could reasonably be considered as base materials for transmission gears. The experimental tests highlighted that, under lubricated conditions, the RCF resistance of the WC/C-coated steel gears was higher than that of the case-hardened ones and, therefore, the PVD WC/C coating could be taken into account to improve the RCF behaviour of these components.

References

[1] Stewart S, Ahmed R. Rolling contact fatigue of surface coatings-a review. *Wear* 2002; 235:1132–1144.

[2] Kim KR, Suh CM, Murakami RI, Chung CW. Effect of intrinsic properties of ceramic coatings on fatigue behavior of Cr-Mo-V steels. *Surf Coat Technol* 2003; 171:15–23.

[3] Baragetti S, La Vecchia GM, Terranova A. Variables affecting the fatigue resistance of PVD-coated components. *Int J Fat* 2005; 10–12(27):1541–50.

[4] Baragetti S. Fatigue resistance of steel and titanium PVD coated spur gears. *Int J Fat* 2007; 29:1893–903.

[5] Cunha L, Andritschky M, Pichow K, Wang Z. Microstructure of CrN coatings produced by PVD techniques. *Thin Solid Films* 1999; 355–356:465–71.

[6] Baragetti S, La Vecchia GM, Terranova A. Fatigue behaviour and FEM modelling of thin-coated components. *Int J Fat* 2003; 25:1229–38.

[7] Baragetti S, Cavalleri S, Tordini F. Contact fatigue crack growth in PVD-coated spur gears. *Key Eng Mater* 2010; 417–418:797–800.

[8] Baragetti S, Cavalleri S, Tordini F. A numerical and experimental study of the RCF behaviour of PVD-coated spur gears. *Key Eng Mater* 2011; 452–453:589–92.

[9] ASTM international (Ed.). *ASTM E 112-96. Standard Test Methods for Determining Average Grain Size*. ASTM international, West Conshohocken, Pennsylvania, USA.

[10] Šraml M, Flašker J. Computational approach to contact fatigue damage initiation analysis of gear teeth flanks. *Int J Adv Manuf Technol* 2007; 31:1066–75.

[11] Glodež S, Aberšek B, Flašker J, Ren Z. Evaluation of the service life of gears in regard to surface pitting. *Eng Fract Mech* 2004; 71:429–38.

[12] Kato M, Deng G, Inoue K, Takatsu N. Evaluation of the strength of carburized spur gear teeth based on fracture mechanics. *JSME Int J Series C* 1993; 36(2):233–40.

[13] Murakami Y, Endo M. Effects of defects, inclusions and inhomogeneities on fatigue strength. *Int J Fat* 1994; 16:519–33.

[14] El-Haddad MH, Smith KN, Topper TH. Fatigue crack propagation of short cracks. *ASME J Eng Mater Technol* 1979; 101:42–6.