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Fatigue Resistance of Thin Hard Coated Spur Gears

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Abstract: Aim of this work is to investigate into the possibility of enhancing the fatigue resistance of CrN PVD coated components. In particular PVD coated spur gears were tested and numerical simulation of crack propagation was carried out. The coating layer microhardness and the residual stresses characterising the surface film were measured and the obtained results were introduced in a numerical modelling predicting fatigue life procedure of coated gears used in gearboxes for automotive applications. The number of cycles necessary to reach specified crack depths of coated and uncoated samples was numerically determined and represents a powerful tool to predict fatigue life of coated steel gears. Benefits induced by the presence of coating were pointed out. A sensitivity analysis was carried out too: the effects of the residual stress gradient (evaluated by means of X-ray measurements), and of the elastic properties of bulk material and coating on the fatigue crack propagation were evaluated.

keyword: CrN-PVD, Spur gears, Fatigue resistance, Numerical models, Residual stresses

1 Introduction

Thin hard coatings deposited by means of PVD technique allow to improve both wear resistance and corrosion resistance properties, see VV.AA. (2003) and Barata, Cunha and Moure (2001). This technique has been used for years in order to coat components for mechanical applications of the most various kind, from aeronautical and automotive components to cutting tools and matrices, see Broszeit, Friedrich and Berg (1999). On the one hand, coatings improve tribological properties and prove a good way to protect the material in aggressive environments. On the other hand, the PVD deposition technique may dramatically reduce the fatigue resistance of structural components which are subject to variable loads. The coating-substrate interface represents a weak area, with discontinuous physical and mechanical properties both on the part of the substrate and of the coating. It is subject to a high residual stress field and, if a component surface hasn't been properly prepared, a delamination of the coating as well as fatigue cracks may occur on the surface. Considering, for instance, chromium plated components, in these cases coatings represent a good defence against corrosion, although the life of coated components is shorter than the life of the uncoated ones, see Nascimento, Souza, Pigatin and Voorwald (2001). The residual stress field induced by the presence of coating is maybe the most important parameter to affect fatigue resistance. In the case of compressive surface residual stresses, effects are positive, see Ejiri, Sasaki and Hirose (1997) and Baragetti, La Vecchia and Terranova (2003). Thin coatings have been given a wider interest only for a few years as far as not just wear and corrosion resistance, but also fatigue resistance has become the discriminating parameter in determining the production process of components such as connecting rods, crankshafts, gear wheels and turbine rotors, see Barata, Cunha and Moure (2001) and Suh, Hwang and Murakami (2003). Generally these research works have pointed out increments, in terms of number of cycles and fatigue limit, in coated components with respect to the uncoated ones. Fatigue behaviour is enhanced by high residual stresses induced by this treatment, see Gelfi, La Vecchia, Lecis and Troglio (2005) and Murotani, Hirose, Sasaki and Okazaki (2000). On the one hand it is well-known that from a phenomenological point of view properly "designed" coatings can enhance fatigue resistance. On the other hand, the choice of the type of coating (its chemical composition in particular), of the deposition technique and of thickness is frequently based on empiric considerations or on the operator's experience, see Ichimura and Ando (2001). In order to choose optimal coating parameters it would therefore be necessary to develop a model to assess the variation sensitivity of coating parameters on

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the effects caused on fatigue resistance. Literature offers many studies, both experimental and numerical, dealing with mechanical properties of the surface of thin hard coated components. However, only a few works take fatigue resistance into consideration in terms of variation of the threshold stress intensity factor range and of the crack propagation after nucleation located at the coating or at the coating-substrate interface. In some articles fatigue crack propagation was simulated with the boundary element method, see Takahashi and Shibuya (1997). Furthermore, finite-element modelling enabled simulation of nanoindentation processes in order to gather detailed information on hardness and fracture toughness, see Souza, Mustoe and Moore (1999) and Dejun, Kewei and Jiawen (1998). A numerical model enabling simulation of the coating presence on four-point bending tests was developed by the authors, see Baragetti, La Vecchia and Terranova (2003). This model makes it possible to predict the number of cycles until failure of specimens with surface defects on the coated region. The model was optimised for laboratory specimens and should be "exported" for the application on thin hard coated components. This paper takes into consideration a steel spur gear used in the automotive industry, see Guagliano and Vergani (2001). At first the numerical approach was applied in order to assess whether the thin coating, which was chosen to coat the gear (PVD, thickness 4 μm), could enhance fatigue resistance at the teeth base of the component. The numerical model developed needs assessment of the mechanical properties of the gear material and of the coating, of the residual stress field induced by the PVD technique both in the coating and in the substrate, of the microhardness trend both in the coating and in the substrate. The model may be analysed only in absence of delamination between coating and substrate. The only defects which could be simulated are therefore the ones caused by irregularities on the coating-substrate interface. They can be simulated as cracks propagating with a path perpendicular to the surface of the component. Such hypothesis is substantiated only if the component surface has been properly prepared before coating; some studies pointed out that, by preparing the surface finishing of the component before treatment, no delamination will occur, see Cunha and Andritschky (1999). Analyses carried out showed that the residual stress field deeply affects propagating cracks at the coating-substrate interface of the spur gears under consideration. The variation sensitivity of the residual stress field induced by the treatment on fatigue crack propagation growth rate was analysed to show that the determining parameter is the residual stress in the coating thickness (even though it is barely 4 μm). The choice of the substrate material is another critical step to guarantee a specific lightness of the component; the next step in this study will be the evaluation of the possibility to coat spur gears made of aluminium or titanium, while considering fatigue resistance at the teeth base as well as on the surface.

2 Geometry and material of spur gears

The present paper takes into consideration spur gears which compose the gearbox of an average swept volume car. Tab. 1 shows the geometric properties of the gears, see Fig. 1a.

The material used for spur gears is steel 18NiCrMo5 (UNI 7846) and gears were casehardened. The effective thickness of the treatment is 1 mm, see La Vecchia (2005). The chemical composition of steel is shown in Tab. 2, see La Vecchia (2005).

Hardness measurements of uncoated gears (diamond conical indenter with an apex angle of 120°, with an applied load of 100 N per 8 s), taken on the sides, at the head and at the base of the teeth, and on the lateral surfaces of the gears, provided an average value of 55 HRC. Roughness measurements, taken with a portable profilometer DIAVITE DH-5, provided an average value of R_a=0.67 μm (Fig. 1b). Residual stresses measurements (diffractometer D/max RAPID Rigaku), taken on tooth tips and near the base of the spur gears, as far as uncoated gears are concerned, provided an average value of –200 MPa, see La Vecchia (2005).

2.1 Coating properties

Spur gears have been coated with chromium nitrade (CrN) deposited by means of PVD technique. The coating thickness is 4 μm. The coating elastic modulus is E=303 GPa, while the Poisson's ratio is ν=0.2, see Baragetti, La Vecchia, and Terranova (2005). Roughness measures, taken with a portable profilometer *DIAVITE DH-5*, provided an average value of R_a=0.91 μm. Residual stresses measures (diffractometer *D/max RAPID Rigaku*), taken on tooth tips and near the base of coated spur gears, provided an average value of –1200 MPa, see La Vecchia (2005). Since the penetration of the RX beam is 10 μm, residual stress values which were

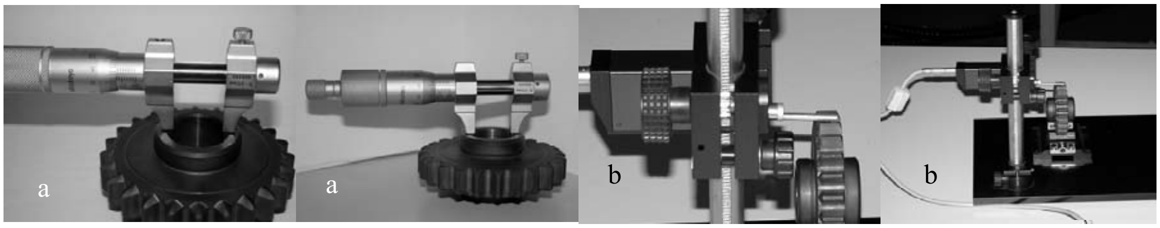

Figure 1 : a) measurement of the dimensions of spur gears and b) roughness measures

Table 1 : Geometric properties of spur gears

Modulus m [mm]	**Number of Teeth of the Pinion Z_1**	**Number of Teeth of the Gear Z_2**	**Thickness B** [mm]	**Normal Angle Pressure α**	**Angle of Pressure at the Most External Single Point of Contact α_{en}**
2.95	11	24	13.3	22 °	25 ° 2’ 53”

Table 2 : Chemical composition of steel 18NiCrMo5

%**C**	%**Mn**	%**Cr**	%**Ni**	%**Mo**	%**Si**	%**S**	%**P**	%**Al**
0.16	0.9	1.0	1.3	0.2	0.27	0.19	0.015	0.031

measured do not refer only to the coating (which however presents some residual stress gradient). Residual stress measurements on coated gears taken at the depth of the bulk material provided an average value of –40 MPa. The value of the actual residual stress of the coating will therefore be approximately –2500 MPa, which is a typical value for such coatings (from 0,8 GPa to 3 GPa in function of the substrate material, see Djouadi, Nouveau, Banakh, Sanjinés, Lévy and Nouet (2002)). Microhardness measurements carried out by the authors, see Baragetti, Gelfi, Lecis and La Vecchia (2005) on the same coating, but respectively on 2205 duplex stainless steel and H11 tool steel, showed that surface hardness is approximately 2500 HV. Hardness at the coating-substrate interface corresponds to the average value of the hardness of the substrate and of the coating. As far as coated spur gears are concerned, surface hardness is therefore the same as in Baragetti, Gelfi, Lecis and La Vecchia (2005), while for the substrate the hardness typical of casehardening steel was used (300 HV), see Cischino (1995-1996). The coating proved a good adhesion, i.e. absence of delamination, with the substrate.

3 Numerical models

A numerical finite element model, supported by analytical models available in literature, enabled to evaluate the propagation growth rate of cracks on the coating, at the coating-substrate interface, at the base of spur gear teeth perpendicularly to the surface. The good adhesion between coating and substrate confirmed the necessity to simulate only the propagation of cracks with a path perpendicular to the surface.

Here is the procedure: the numerical model enables one to calculate the stress intensity factor range (in a “discrete” way, for each value of crack depth) and to compare it with the threshold stress intensity factor range (obtainable from previously published models). If the stress intensity factor range is higher than the threshold stress intensity factor range, crack propagation is possible. If the crack propagates, then the fatigue crack growth rate can be evaluated by means of existing models developed for casehardened spur gears, see Par. 3.1. As a consequence the number of cycles necessary to reach specific crack depths is also evaluated. Several crack depths were simulated: 4 μm, 25 μm, 50 μm, 100 μm, 190 μm, 300 μm, assuming that the crack will not change its path while propagating. The number of propagation cycles with and without coating was then compared.

The numerical-analytical calculation procedure was supported by the authors by means of experimental tests in the case of four points bending tests, see Baragetti, La Vecchia and Terranova (2003).

3.1 Evaluation of crack propagation growth rate

The value of the threshold stress intensity factor range can be evaluated by means of the crack micro-mechanics models (MFM). Literature offers Murakami's model, see Murakami and Endo (1994), based on the collection of experimental data on three-dimensional short cracks (R= $\sigma_{min}/\sigma_{max}$= -1):

$$\Delta K_{th} = 3.3 \cdot 10^{-3} (HV + 120) \left(\sqrt{Area}\right)^{1/3} \left(\frac{1-R}{2}\right)^{\psi} \quad (1)$$

$$\psi = 0.226 + HV \times 10^{-4} \quad (2)$$

The parameter $\sqrt{Area}$ [mm], in the case of fragile coatings, may be considered equal to the depth of the crack. This model to assess the threshold stress intensity factor range may be applied only if the crack length meets the inequality $3a_0 < a < 10a_0$. The parameter a_0 has a physical meaning: it represents the maximum depth at which the crack is not affected by microstructural barriers (usually a high hardness phase in a soft material matrix), see Miller (1982) and El-Haddad, Smith and Topper (1979).

$\Delta K_{th,Ic}$ is the threshold stress intensity factor range for long cracks in [MPa$\sqrt{m}$], β is the shape factor, σ_{w0} is the fatigue limit of the material. ΔK_{th} is constant for $a > 10a_0$. Propagation growth rate beyond the threshold, in case of coated and hardened surfaces, can be calculated by means of the literature models developed for casehardened spur gears, see Guagliano and Vergani (2001) and Kato, Deng, Inoue and Takatsu (1993). Microhardness trend and stress intensity factor (which can be calculated by means of finite element modelling) have to be calculated in order to apply such models.

$$a_0 = \left(\frac{\Delta K_{th,Ic}}{\beta \Delta \sigma_{w0}}\right)^2 \frac{1}{\pi} \quad (3)$$

$$\begin{aligned}
\frac{da}{dN} &= \frac{C}{(1-\rho^n)}(\Delta K^n - \Delta K_{th}^n) \quad \text{for } \Delta K_{th} \le \Delta K \le K_C \\
\frac{da}{dN} &= \frac{C}{(1-\rho^n)}\left(\frac{\Delta K^n K_{Ic}}{\Delta K_{Ic}^n - \Delta K^n}\right) \quad \text{for } K_C < \Delta K < K_{Ic} \\
\rho &= \frac{\Delta K_{th}}{K_{Ic}}, \quad K_C = (\Delta K_{th} K_{Ic})^{1/2} \quad (4)
\end{aligned}$$

The terms of the expressions (4) have the following meaning:

$$\begin{aligned}
A &= -\frac{1}{d_2^2} \ln\left(\frac{H_1 - H_3}{H_2 - H_3}\right) \quad d^* \le d_2 \\
A &= -\frac{1}{(d_c - d_2)^2} \ln\left(\frac{550 - H_3}{H_2 - H_3}\right) \quad d^* > d_2 \\
H &= (H_2 - H_3) \exp\left[-A\,(d^* - d_2)^2\right] + H_3 \\
\Delta K_{th} &= 2.45 + 3.41 \cdot 10^{-3} H \\
K_{Ic} &= 141 - 1.64 \cdot 10^{-1} H \\
n &= 4.31 - 8.66 \cdot 10^{-3} H + 1.17 \cdot 10^{-5} H^2 \\
\log(C) &= -10.0 + 1.09 \cdot 10^{-2} H - 1.40 \cdot 10^{-5} H^2 \quad (5)
\end{aligned}$$

d_c = thickness of coating [mm]
d_2 = depth of maximum hardness data [mm]
d^* = depth from the surface [mm]
H_1 = surface hardness [HV]
H_2 = maximum hardness [HV]
H_3 = core hardness [HV]
H_4 = hardness at the coating-substrate interface [HV]

3.2 Finite element models

The finite element model is shown in Fig. 2b. This model does not allow to simulate the mesh between gear and pinion. Nevertheless it enables to reproduce the laboratory tests conditions as described in Par. 4 (the roller is the rolling element of a bearing in 100Cr6 with a surface hardness of 60 HRC), see Guagliano and Vergani (2001). The bending action induced by the mesh on the teeth is actually simulated by the action of a roller being forced between two teeth at the most external single point of contact, see Fig. 2a. The model was carried out with plane finite elements which reproduce a behaviour in a plane stress state. Two teeth were modelled and, thanks to the symmetry of this issue, only one half of the cylinder and of the two teeth was reproduced for finite elements, see Fig. 2b. Constraints such as void movements perpendicular to the surface (e.g. rolling joints) imposed on the left border surface of the model, see Fig. 2b, do not reproduce the actual constraint of the teeth at the remaining part of the spur gear. We did not reproduce the whole spur gear not to make the model too heavy. However the crack is located at the tooth fillet, far from the constraints, in the area where the highest bending stresses occur. The simplified formulation of a model is also due to the fact

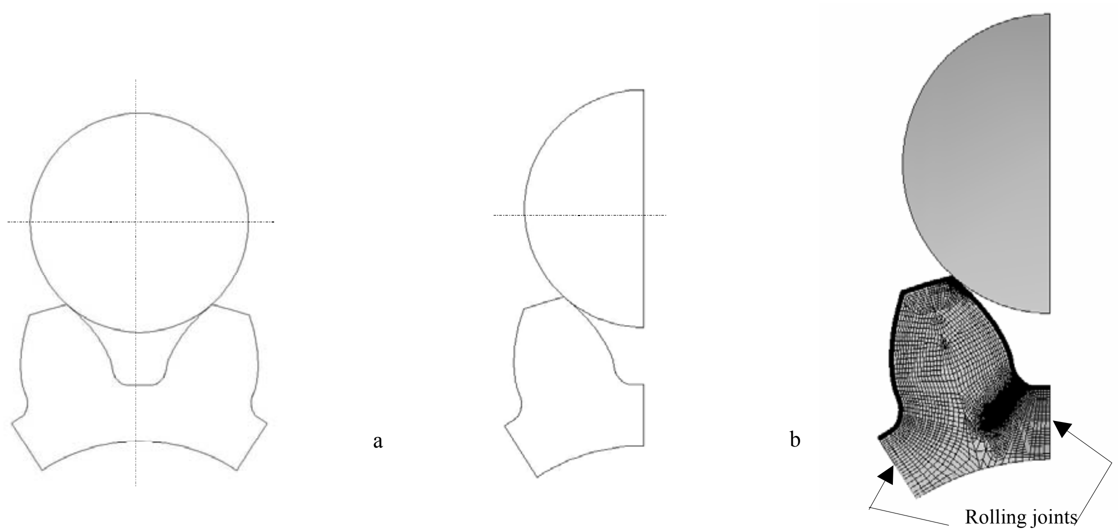

Figure 2 : a) load application method and b) FEM model

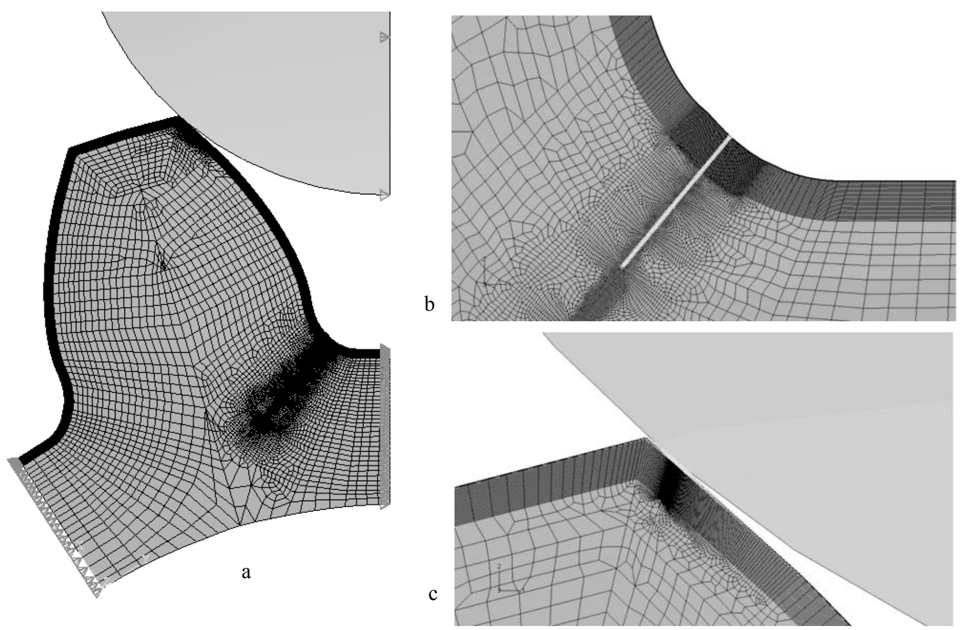

Figure 3 : a) FEM model of the coated tooth presenting a crack, b) particular of the coating and of the crack in the FEM model, c) particular of the contact area between roller and tooth

that the aim of this paper is to assess whether the presence of the coating may enhance the life of the coated spur gear with respect to the uncoated one (the key factor is therefore that models shall be identical).

The modellator used is the MSC-Patran 2004, the solver is the Abaqus 6.4. Analyses with elastic linear material behaviour were carried out while the plasticization at the crack tip was neglected.

Application of residual stresses was carried out by means of a temperature gradient procedure: a specified temperature profile, with nodal temperature from surface to the inside, enabled simulation of the presence of the residual stress profile obtained by means of experimental measures, see Fig. 4. The residual stress profile was obtained by knowing only the surface residual stress and by setting a balanced profile. The authors verified that trend varia-

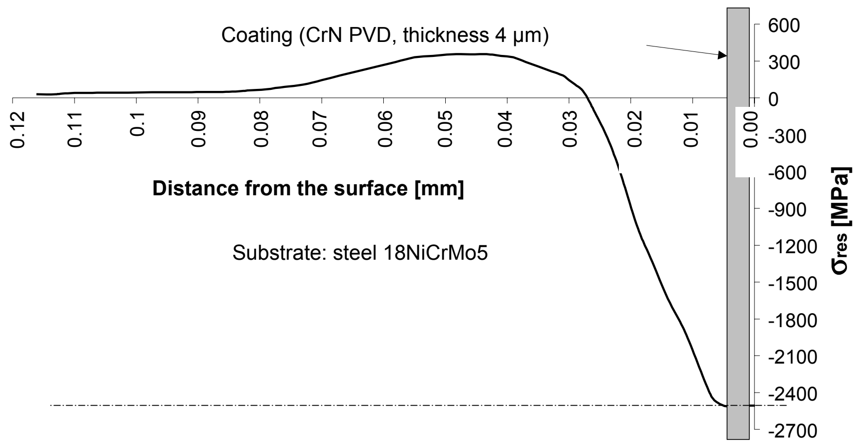

Figure 4 : Residual stress profile applied to the FEM model

tions in the residual stress profile do not significantly affect the stress intensity factor range obtained by means of the FEM model due to the high residual stress value on the surface. The applied load is relatively high (the cylinder which stresses two teeth was applied a vertical force of 52000 N generating the highest stress of 1500 MPa at the tooth base).

$$K_I = 2G\sqrt{\frac{2\pi}{r}}\frac{u}{f(\theta)}$$
$$f(\theta) = \sin\left(\frac{\theta}{2}\right)\left[k+1-2\cos^2\left(\frac{\theta}{2}\right)\right] \qquad (6)$$

A pulsating load from zero was simulated. The stress intensity factor range ΔK was calculated by means of the relative offset values of the cracks flanks (θ is the angular position with respect to the propagation direction, E is the elastic modulus of the material, ν is the Poisson's ratio, r is the distance from the crack tip, u is the half of the relative displacement between the flanks of the crack):

In (6) $k = 3-4\nu$ in plane stress state while $k = (3-\nu)/(1+\nu)$ in plane deformation state.

Tab. 3 and 4 show the values of ΔK_{eff} = (ΔK_I - ΔK_{res}), taking into consideration the effect of the residual stress field, respectively for the uncoated and the coated gear. Due to the high deposition temperature, the PVD treatment eliminates the positive effects, in terms of residual stress, induced by the casehardening treatment. The authors verified that both shot-peened and PVD-coated specimens show the same behaviour, see Baragetti, La Vecchia and Terranova (2003).

The analysis of Tab. 3, regarding the uncoated gear, shows that cracks may propagate ($\Delta K_{eff} > \Delta K_{th}$) only if their depth is over 4 μm. The analysis of Tab. 4, regarding the coated gear, shows that cracks may propagate ($\Delta K_{eff} > \Delta K_{th}$) only if their depth is over 25 μm. ΔK_{eff} for the CrN-coated gear shows relevant values only if the crack depth is over 25 μm. Furthermore, ΔK_{eff} has approximately the same value at 300 μm both for the coated and for the uncoated gear; this means that the positive effect of residual stresses induced by the presence of the coating cannot be detected at higher depths and that the behaviour with or without coating is the same for crack depths over about 200 μm. Tab. 5 shows the number of cycles necessary to reach the same crack depths in the casehardened and in the CrN-coated gear respectively.

The analysis of Tab. 5 shows that, as far as the coated gear is concerned, a surface crack lower than 25 μm cannot propagate, while in the casehardened gear the propagation occurs, due to the applied load, with cracks over or equal to 4 μm. As far as the coated gear is concerned, for the crack to propagate up to 300 μm the number of cycles must be 111694 with respect to 3098 cycles for the uncoated gear. The positive effect induced by the presence of the coating shows clearly. Most cycle numbers are required to go from 25 μm to 50 μm for the coated gear; on such cracks the positive effects of residual stresses on the surface are stronger, as they reduce the propagation growth rate of these cracks.

If the residual stresses field induced by the treatment is not applied, the numerical model of the coated gear requires the same number of cycles as the casehardened gear. The residual stress field induced by the PVD treatment is therefore the crucial factor determining the in-

Table 3 : Evaluation of ΔK_{eff} for the casehardened uncoated gear

Crack Depth *[μm]*	***Hardness*** *[HV]*	***Node Distance*** $[m]$	***u*** $[m]$	$\boldsymbol{u_{res}}$ $[m]$	$\boldsymbol{\Delta K_I}$ $[MPa\sqrt{m}]$	$\boldsymbol{\Delta K_{res}}$ $[MPa\sqrt{m}]$	$\boldsymbol{\Delta K_{eff}}$ $[MPa\sqrt{m}]$	$\boldsymbol{\Delta K_{th}}$ $[MPa\sqrt{m}]$
4	600	1,E-06	3.436E-08	0.0E+00	5.62	0.00	5.62	3.33
25	600	5,E-06	2.141E-07	0.,0E+00	15.65	0.00	15.65	4.50
50	600	5,E-06	2.953E-07	0.,0E+00	21.59	0.00	21.59	4.50
100	600	5,E-06	3.897E-07	3.34E-10	28.49	0.00	28.49	4.50
190	600	5,E-06	4.757E-07	5.61E-10	34.77	0.00	34.77	4.50
300	600	5,E-06	5.231E-07	5.78E-10	38.24	0.00	38.24	4.50

Table 4 : Evaluation of ΔK_{eff} for the CrN-coated gear

Crack Depth *[μm]*	***Hardness*** *[HV]*	***Node Distance*** $[m]$	***u*** $[m]$	$\boldsymbol{u_{res}}$ $[m]$	$\boldsymbol{\Delta K_I}$ $[MPa\sqrt{m}]$	$\boldsymbol{\Delta K_{res}}$ $[MPa\sqrt{m}]$	$\boldsymbol{\Delta K_{eff}}$ $[MPa\sqrt{m}]$	$\boldsymbol{\Delta K_{th}}$ $[MPa\sqrt{m}]$
4	1600	1,E-06	1.62E-09	0.0E+00	0.27	0.00	0.27	7.62
25	300	5,E-06	4.11E-09	0.0E+00	0.30	0.00	0.30	3.44
50	300	5,E-06	1.09E-07	8.71E-10	8.00	0.06	7.94	3.20
100	300	5,E-06	3.15E-07	4.74E-08	23.07	3.47	19.60	3.49
190	300	5,E-06	4.38E-07	3.62E-08	32.02	2.65	29.38	3.49
300	300	5,E-06	4.94E-07	2.51E-08	36.13	1.84	34.29	3.49

Table 5 : Number of cycles for the casehardened gear and for the CrN-coated gear

	Crack Depth *[μm]*	***Number of Cycles***		***Crack Depth*** *[μm]*	***Number of Cycles***
Casehardened spur gear	4 – 25	2580	***CrN coated spur gear (4 μm)***	4 – 25	No propagation
	25 – 50	266		25 – 50	106777
	50 – 100	145		50 – 100	3506
	100 – 190	75		100 – 190	924
	190 – 300	32		190 – 300	487
	Total Number of Cycles	***3098***		***Total Number of Cycles***	***111694***

crease in the number of cycles for the coated gear when the propagation depth is the same.

4 Experimental investigations

A test device was developed in order to carry out bending tests on the gear teeth under consideration in this paper, see Cischino (1995-1996). Fig. 5 shows the three-dimensional assembly drawing of the system and a picture of the system mounted on a 100 kN Galdabini universal test machine.

The microscopic examination of the gears after preliminary tests and the use of liquid penetrants showed that both on the casehardened and on the CrN-coated gear no fatigue crack propagation occurred at the teeth base (the applied load is the same as the one used in FEM models). Without any surface crack, no fatigue crack propagation shall occur on the CrN coating according to these models, see Par. 3.2. However, for casehardened gears, a crack may propagate up to 300 μm after approximately 3100 cycles in the case of surface cracks which are over 4 μm deep. This result is probably due to the absence of cracks in the most stressed area of the specimens (the numerical model developed allows to predict the number of cycles necessary to go from a specific crack depth to a wider one only if the crack is already present on or near

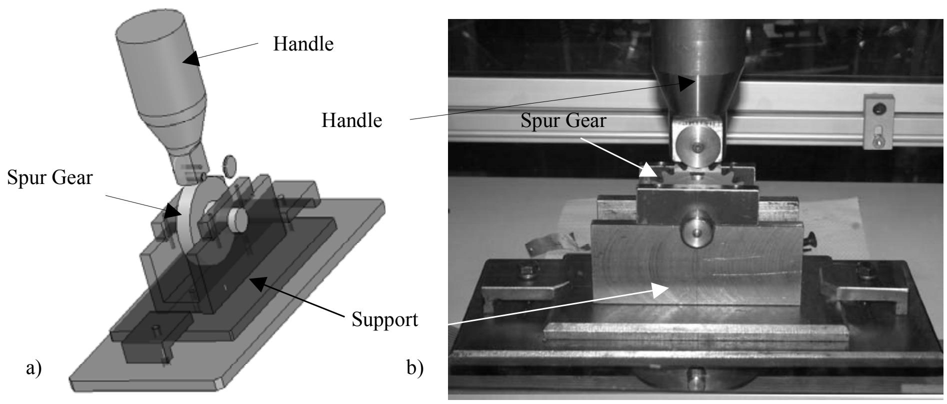

Figure 5 : a) three-dimensional assembly drawing of the test system and b) picture of the test system mounted on a 100 kN Galdabini universal test machine

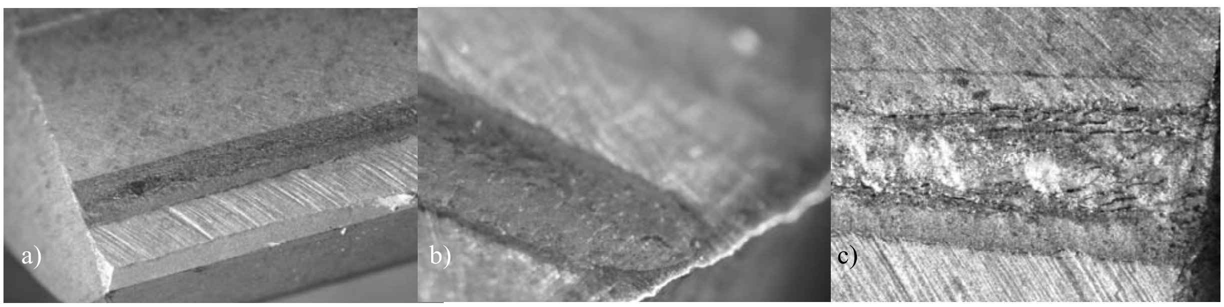

Figure 6 : Pictures of the contact point of the tooth roller-side after tests on casehardened gears

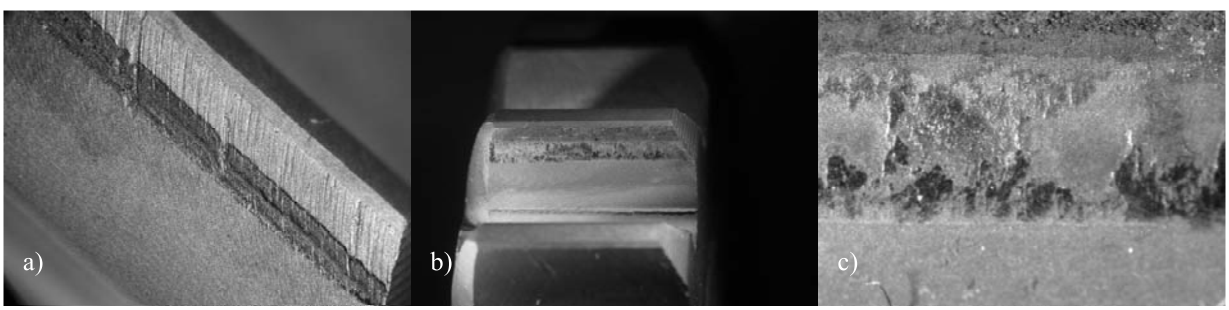

Figure 7 : Pictures of the contact point of the tooth roller-side after tests on CrN-coated gears

the surface).

The analysis of the contact points between rollers and teeth sides allows to formulate some hypotheses on the surface fatigue resistance, even though the test device is not suitable for surface fatigue tests. The pictures of the contact points after high load tests on casehardened gears are shown in Fig. 6, while Fig. 7 shows the damaged surfaces of CrN-coated gears.

By comparing the pictures shown in Fig. 6 and 7 we can see that impressions on the sides of coated teeth have a darker colour, which is probably due to the lower oxidation. Furthermore they show a black/anthracite coloured profile, which is supposedly the coating thickness. During the test on the coated gear, see Fig. 7c, a delamination of the material occurred (CrN coating), which did not occur on the uncoated gear. This phenomenon is surely due to the high test load, which caused excessive damage on the contact point, i.e. the delamination of chromium nitride.

5 Conclusions

A numerical procedure was developed to predict fatigue life of thin coated spur gears, for automotive applications, coated by means of the PVD technique (CrN with a thickness of 4 μm). The evaluation of the stress intensity factor and the use of models developed in previous works to simulate fatigue crack propagation allowed to model the propagation of a surface crack. The procedure developed, which was experimentally substantiated by the authors in their previous works, can by applied to any kind of coating, as long as a good adhesion to the underlying material is guaranteed in order to enable the crack to propagate from the coating to the substrate. Numerical results show that in the presence of the thin hard coating there is a relevant enhancement in the number of cycles necessary to let a crack propagate (a crack on the surface of the most stressed area of the gear at the teeth base) up to a predetermined depth. The enhancement in the fatigue limit of coated gears is mainly due to the residual stress field induced by the PVD treatment.

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