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Prediction of the critical load of a metal-rolling system by considering the damage of the coated surface

Jiling Feng[1)], Yi Qin[1)], Massimo Lorusso [2)], Daniele Ugues[2]

[1)]Dept. of Design, Manufacture and Engineering Management, University of Strathclyde, Glasgow, G1 1XJ UK; Jiling.feng@strath.ac.uk; or Qin.yi@strath.ac.uk; [2)]Politecnico di Torino, Torino, Italy

Abstract. Under various working conditions, rolling elements may suffer from different types of damage behaviour, including fractures in the coatings and bonding interfaces, and plastic deformation in the substrate materials. The present paper reports research into the prediction of the critical load of a metal-rolling system (metal-rolling system) by considering the damage of the coated surface based on a novel FE simulation-procedure developed by the present authors. The modelling procedure features several modelling approaches including: parameterised FE modelling, Cohesive-Zone modelling and a sub-modelling technique. The typical case examined in this study is line-contact between two cylindrical bodies. The studied surface-modified systems are CrN, TiN and TiN/CrN multilayer PVD coatings applied on 42CrMo4 steel in both the nitrided and quenched-and-tempered states.

It was observed through the numerical simulation that for almost all of the configurations, cracking occurs at the edge of the contact when one cylinder is pressing against the other cylinder, due to a bending effect. The critical load of the system was determined by referring to the initiation of the first crack of the coated surface of the ring. Comparison between the numerical-simulation results and the experimental results showed excellent agreement.

Keywords: Coating, Surface, Metal-rolling system, Cohesive-zone Model,

1. INTRODUCTION

Hard coatings on rolling-contact elements have been used widely in various industries, including those involved in mechanical-transmission systems and manufacturing processes such as precision shape-rolling, due to the demands for improved mechanical and tribological properties. Under various working conditions, the rolling elements may suffer from different types of damage behaviour, including fractures in the coatings and bonding interfaces, and plastic deformation in the substrate materials. An example of the surface cracks of rolling-contact elements under the action of rolling-contact fatigue is shown in figure.1.

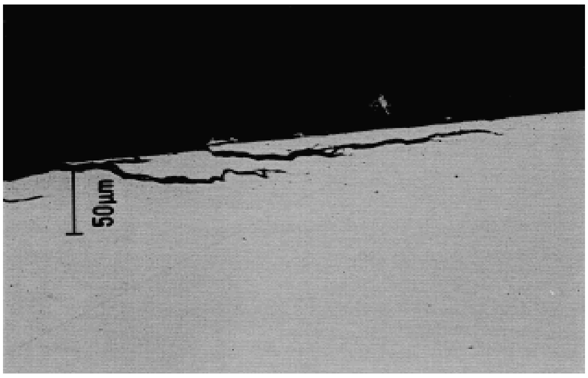

Figure 1 Surface cracks in the inner ring under rolling-contact fatigue. (Source ref. [1])

Previous research, driven by the need to improve the life of rolling-elements, was, mostly, focused on the characterisation of rolling-contact fatigue by means of experimental tests [2]. Theoretical and numerical research regarding damage analysis for coated rolling-components is limited. To date, a numerical model for the damage analysis of the coated rolling-components, has not been available, although a few research investigations have been dedicated to failure analysis and coating design for rolling components such as spur gears and bearings [3-5], using a computational model. A novel comprehensive FE simulation procedure was developed recently by the present authors [6], allowing for a variety of types of failure behaviour of multilayered coating surfaces under different working conditions to be analysed. This modelling procedure has been validated by a series of indentation tests [7] applied under various working conditions [8].

This paper reports research into the prediction of the critical load of a metal-rolling system by considering the damage of the coated surface based on this novel FE simulation procedure. The modelling procedure is combined with several modelling approaches including: parameterised FE modelling which allows variations of material and geometrical parameters and loading conditions to be considered in the analysis; Cohesive-Zone modelling to enable the simulation of the initiation and propagation of the cracks in the coating-layer to be observed physically; and a sub-modelling technique to help in scaling down the geometry of the global model from the macro-scale to the micro/nano-scale, in order to be able to study the performance of the coated system in detail.

The typical case examined in this study is line-contact between two cylindrical bodies (refereed as a "ring-to-wheel" system), which is assumed to be an accurate representation of some typical rolling-contact systems. One of the cylinders, the "ring", was surface modified with mono and multilayered systems. The studied surface-modified systems are CrN, TiN and TiN/CrN multilayer PVD coating applied onto 42CrMo4 steel in both the nitrided and quenched-and-tempered states.

It was observed through the numerical simulation that for almost all of the configurations, cracking occurs at the edge of the contact when one cylinder is pressed against the other cylinder, due to a bending effect. The critical load of the system was determined by referring to the initiation of the first crack of the coated surface of the ring.

The simulation results have been compared with the experimental results.

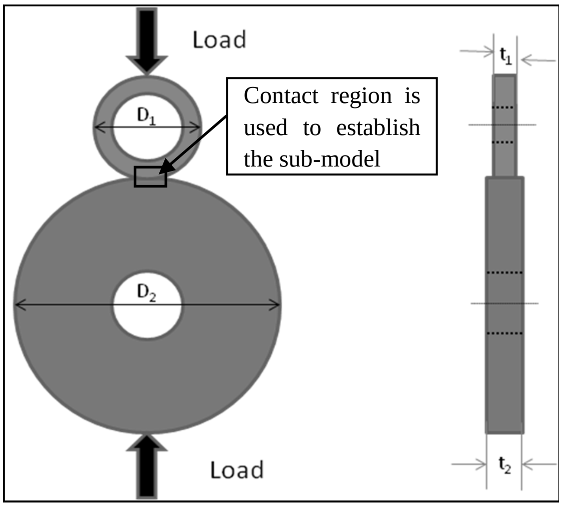

Figure.2 Scheme of the line-contact rolling-contact system, where D1 and D2 indicate the diameter of the ring and the wheel, respectively; and t1 and t2 indicate the widths of the ring and the wheel, respectively.

2. METHODOLOGY

A continuum-mechanics FE model is developed with a new modelling procedure which combines a sub-modelling technique, a parameterised-modelling approach and Cohesive-Zone modelling.

2.1. Sub-modelling technique

The sub-modelling technique, available in Abaqus, was used to study a local part of a model with a refined mesh based on the interpolation of the solution from an initial relatively-coarse global model. In this work, the sub-modelling technique is used to help in scaling-down the geometrical model of the rolling-contact system from the macro-scale to the micro/nano-scale, in order to be able to study the performance of the coated system in detail. The case examined in this study is line-contact between two cylindrical bodies (referred to as a "ring-to-wheel" system) (figure.2). In this ring-to-wheel model, there is a significant difference in dimensions between the two wheels (60mm diameter for the large wheel and 24mm for the ring) and coating thickness (2μm), which causes difficulty in the establishing of a unified model to consider different length scales. To address this problem, a two-step analytical procedure is used: (1). Determine the contact conditions (pressure and friction) in the contact area using the global model; and (2). Use a sub-model to represent the contact region in which the micron-scale coating is considered, as well as incorporation of cohesive elements for the prediction of the damage development.

2.2. Cohesive-zone modelling

As aforementioned, the aim of this paper is to predict the critical load of the metal-rolling system by considering the damage of the coated surface. In this paper, the cracks of the coated surfaces are simulated by means of the cohesive-zone model in the sub-model.

According to the cohesive law, the cohesive tractions between the adjacent virtual-crack surfaces, which are originally produced due to the inter-atomic forces, work as the resistance against the separation of two surfaces. Under the external loading conditions, the distance between the atoms changes and the inter-atomic tractions decrease once the maximum traction is reached. At the moment when the interfacial tractions start to decrease, the two adjacent and opposite surfaces separate from each other completely, defining the formation of a macroscopic crack in the coating.

Over recent decades, a variety of forms of the cohesive law, distinguished by the softening relationship of the traction—separation, including exponential [9] and bilinear [10] functions, has been used widely to analyse fracture performance [11-12].

In this paper, the cohesive-zone model is implemented between the continuum elements in the sub-model and the irreversible bilinear cohesive-zone model is employed to simulate the initiation and propagation of the cracks of the coated surface under the contact pressure and surface traction (figure.3). The bilinear cohesive constitutive law can be written as:

$$G_c = \frac{1}{2} T_{\max} \delta_c \qquad (1)$$

where: G_c is the critical energy-release rate governing the damage evolution and T_{max} indicates the maximum traction; and δ_c is the characteristic cohesive-zone length to which the separation reaches when the crack surfaces will be generated. A crack in the coating layer may be initiated when the separation reaches the critical value of δ_{max}, at which point the traction achieves its maximum value, T_{max}. More details regarding the bilinear cohesive constitutive law and its applications can be found in the authors' previous paper [6].

2.3. Parameterised modelling

By means of the parameterised-modelling approach, all possible factors associated with the failure behaviour of the coating, such as material properties, geometry and loading history can be defined with the corresponding parameters in the sub-model.

The geometrical model, for example, can be defined by the parameters prescribed as the widths and thicknesses of the coating and the substrate. The mesh scheme can be controlled by the parameters concerning the density of the elements and the dimensions of the model. The element size of the coating in the X-direction, for instance, can be prescribed by dividing its width by the number of element in the same direction in this part. The details of the parameterised modelling approach can also be found in the authors' previous paper [6].

The studied surface-modified systems are CrN, TiN and TiN/CrN nano-multilayer coatings applied onto 42CrMo4 steel substrates. Prior to coating, part of the steel substrates was subjected to active-screen plasma nitriding, whereas the other part was in the simple quenched-and-tempered state. Coating deposition was performed with an industrial Cathodic Arc Evaporation PVD system. In both the FE global and sub-model, the coating and substrate are characterised as being homogenous, with elastic properties followed by linearly-hardening plastic behaviour. The cross-sectional hardness of the hardened layer is converted into the corresponding yield strength. The mathematical function of yield strength versus the depth of the hardened case is obtained by the best-curve fitting- technique and then implemented in the model with the field method. All of the material properties used with this model were provided by the Surface Engineering group in Birmingham University and are presented in Table 1.

Table 1, Material Properties of the Coating and Substrates

Layer	Material	Thickness t (μm)	Hardness H (HV)	Young's modulus E (GPa)	Yield Strength σ_y (GPa)	Poisson's ratio υ	ε_f %	σ_f GPa
coating	TiN	2.00	2500	*300*	4.2	0.27	0.27	4.4
	CrN	2.00	2000	*300*		0.23		
	TiN/CrN	2.00	3500	*300*				
substrate	H11	400.00	446	*203*	1.3	0.3	11.44	1.5
	42CrMo4	400.00	310	*203*	0.989	0.3	16.2	1.1

3. CASE STUDY AND RESULTS

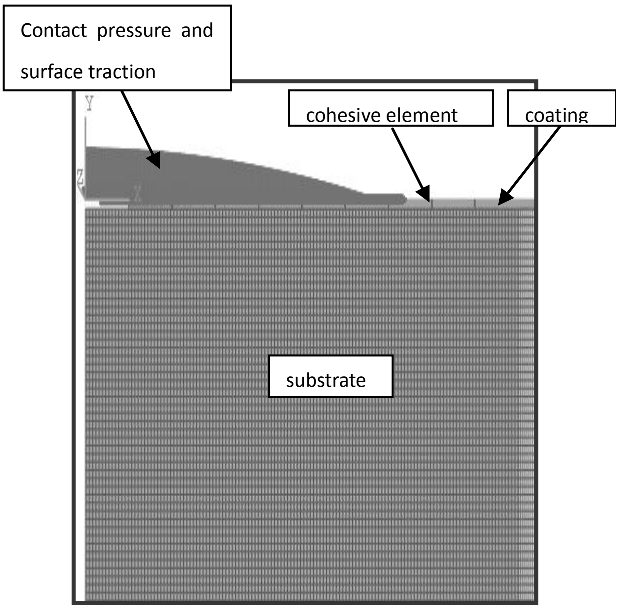

Figure.3 Sub-model representing the contact region in the surface of the ring in the global model, where cohesive-zone elements are placed between each pair of continuum elements within the coating

The FE model for the ring-to-wheel and the FE sub-model representing the contact region of ring are shown in figure.4 and figure.3. Under vertical loading, the contact pressure and surface shear-stresses in the contact region of the ring are obtained through the solution of the global model, as shown in figure.4. With the parabolic distribution of contact pressure and uniform shear-stress that was obtained through the global model, this distribution acting on the surface of the ring in the sub-model causes the surface of the ring to appear to sink downwards towards the substrate (figure.5).

It is shown clearly in this figure that the deep sinking of the contact-zone occurs due to the extension of the plastic zone, which induces the bending of the coating layer. In the surface of the coating immediately outside of the contact zone, tensile stress develops due to the bending of the coating. The cohesive traction in this area increases quickly and approaches its critical value, inducing the initiation of damage. With the further increase of load, the separation between two opposite surfaces of the cohesive-element increases, accompanied by the decrease of the cohesive traction. During this stage, the relationship of traction—separation is governed by the bilinear cohesive-zone model until the two opposite surfaces are completely separated, indicating the occurring of the first crack. The corresponding load associated with the occurring of the first crack is then defined as the critical load for the ring-to-wheel structure. The critical loads for the ring-to-wheel system were studied for a variety of types of surface systems including:

- TiN/CrN coating on quenched-and-tempered 42CrMo4
- TiN coating on quenched-and-tempered 42CrMo4
- CrN coating on quenched-and-tempered 42CrMo4
- TiN/CrN coating on plasma nitrided 42CrMo4
- TiN coating on plasma nitrided 42CrMo4
- CrN coating on plasma nitrided 42CrMo4.

The critical loads associated with the occurrence of the first cracks for a series of mono- and multi-layered surface systems are shown in figure.6. As shown in this figure, for almost all of the configurations, when the ring is pressed against the wheel, the crack occurs at the contact edge of the coating surface of the ring (figure. 5) due to the tensile stresses caused by the plastic deformation of the substrate. The greatest load-bearing capacity is observed for super-lattice coating TiN/CrN on the nitrided 42CrMo4 and the least is for CrN coating on the untreated 42CrMo4. It is shown clearly that pre-heat treatment with plasma nitriding improved the mechanical and tribological properties of the coated surface significantly, which makes the duplex coating surface systems possess a much greater load--bearing capacity than that of single –coating systems..

4. DISCUSSION

The FE model developed in this study was validated through a series of compression tests in the ring-to-wheel configuration. In such tests, different levels of load were applied on the modified surfaces, these loads being the experimental definition of the critical load given as the load at which surface cracks nucleate. Cracks were detected with scanning electron microscopy (SEM) observations.

Figure.7 shows some SEM images of the surfaces of different coated systems subjected to a static compression test in the ring-to-wheel configuration, so as to enable an actual comparison between the simulation and the experimental results. The critical load predicted through FE simulation are in agreement with those observed from SEM images (figure. 8).

The various damage performances, including coating detachment and cracking in the coating surface, were observed from SEM images (figure.7). It has been suggested that surface damage under the action of rolling contact loading are facilited by either extremely high localized contact stresses [13] or plastic deformation [4]. The various damage performances observed in this study, therefore, may be attributed to the different failure-mechanisms at play.

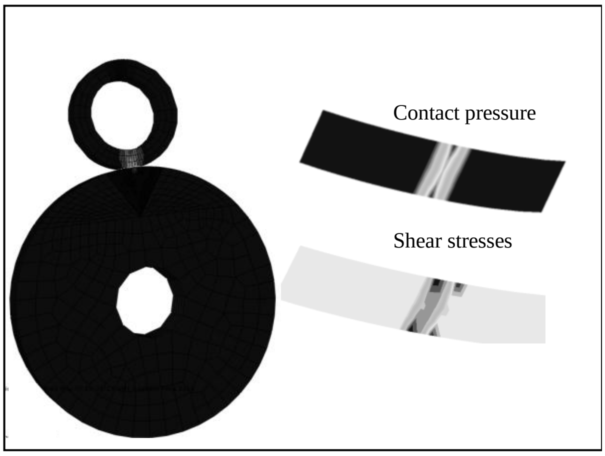

Figure.4 The ring-to-wheel structure and the contact pressure and surface shear-stresses in the contact region of the ring.

With the cases in this study, the greatest load-bearing capacity was observed for superlattic TiN/CrN multilayered coating on the nitrided 42CrMo4. In both the experimental and the numerical results, surface cracks were observed for the TiN/CrN multilayered coating surface on the nitrided 42CrMo4 substrate when the loading reached approximately 6200N. The TiN/CrN multilayered coatings consist of alternative nanometer-scale TiN and CrN layers (bilayer period of 5nm), the superlattic struture of which makes it the hardest coating in this study (Table1), It has been noted previously [6], and also observed in this study (figure.8), that pre-heated treatment with plasma nitriding improved the surface properties dramatically. Therefore, the greatest load-bearing capacity found with the TiN/CrN on nitrided 42CrMo4 is suggested, speculatively, to be due to both the superlattice structure of the coating and the improved properties of the hardened case. The greater load-bearing capacity observed for surface systems with the coatings on the nitrided substrate steel may be due to the lesser dissimilariy of properties between the hardened layer and the coating layers.

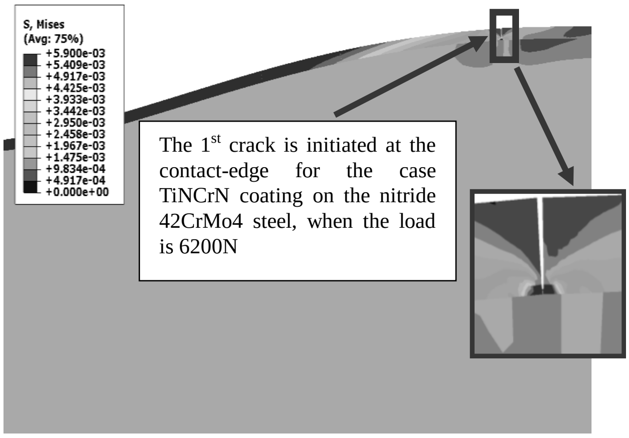

Figure.5 The critical load for ring-to-wheel construction for the case TiN/CrN on 42CrMo4 Nitrided

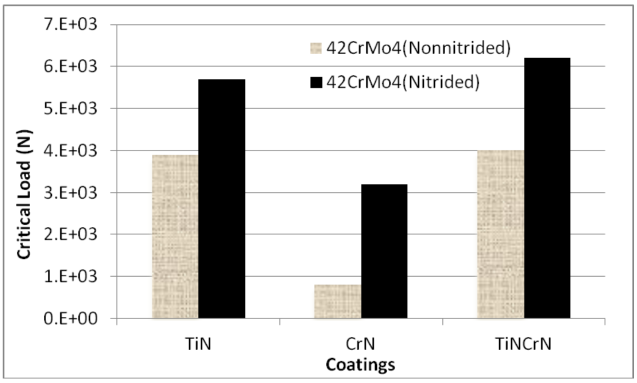

Figure.6 Critcal loads in terms of the occurrence of the first crack in the coating.

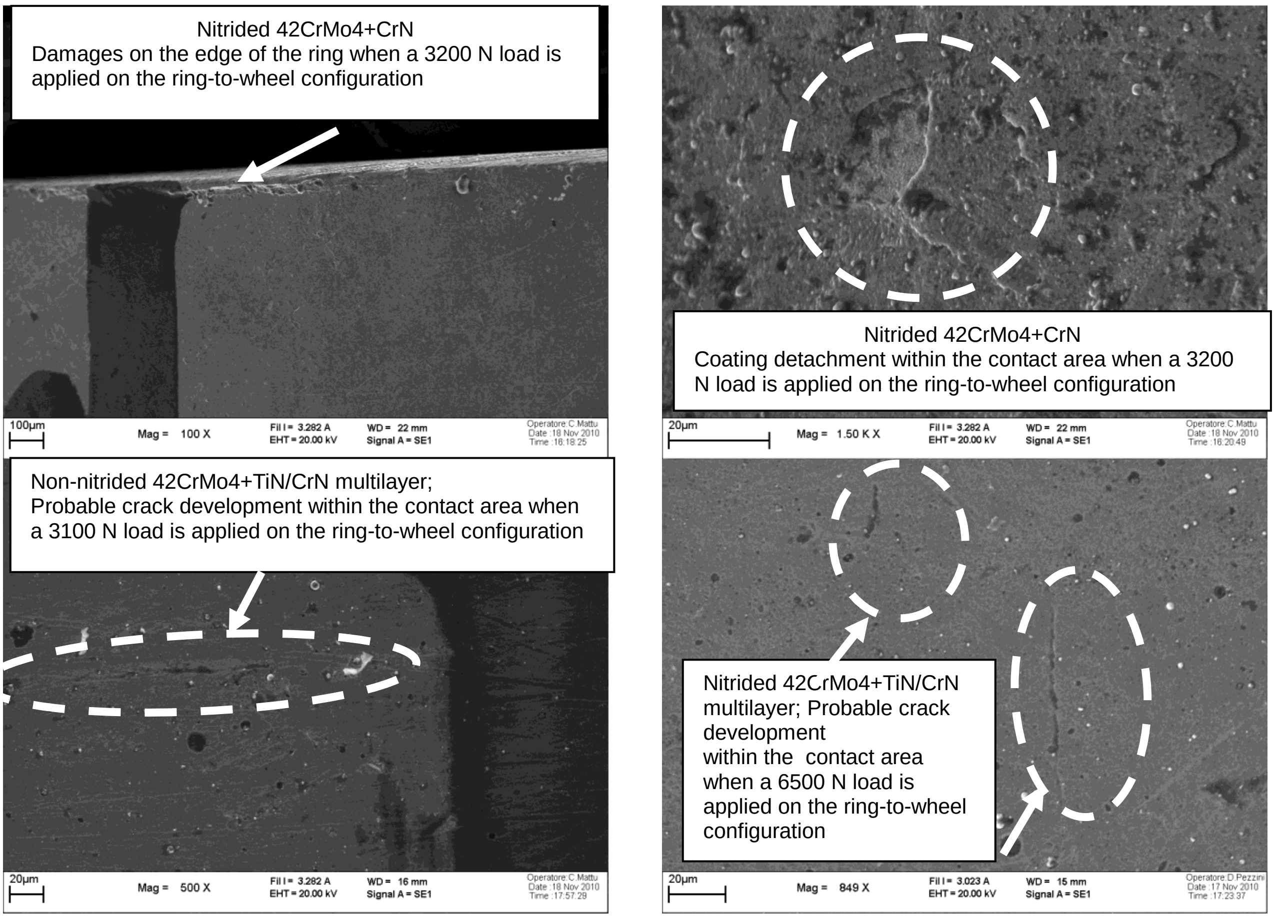

Figure. 7 SEM Images of the edge or the contact area of different coated systems subjected to the static compression test in the ring-to -heel configuration.

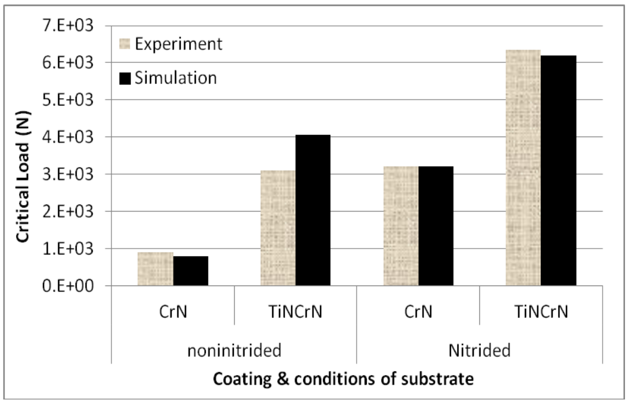

Figure.8. Comparison of the critical load for the Ring-to-Wheel structure between simulation and experimental results

5. CONCLUSIONS

From the FE simulation, for most of the configurations, cracks occurred at the edge of the contact region due to the bending effect of the coatings. The critical loads for the metal-rolling system predicted by referring to the occurrence of the first crack are in agreement with those observed from SEM images. Both experimental and computational results showed that the TiN/CrN nano-multilayer coatings out-performed the monolayer TiN or CrN coating. Duplex coating, formed with the plasma nitriding hardened case, and PVD coatings possess much greater load-bearing capacity than that for single coatings.

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