Surface fatigue resistance of tool steel coated with thin brittle PVD layers

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Surface fatigue properties of tool steel with different PVD coatings have been measured in lubricated rolling contact fatigue (RCF) configuration. The following coatings have been studied: TiN, TiAlN/TiN,TiCN and WC/C. All coatings have been deposited on tool steel by means of Physical Vapour Deposition. The thickness is about 5 μm. The influence of substrate pre treatment and substrate hardness have been investigated. Two values of hardness have been incorporated: 50 HRC and 60 HRC. Three pre treatments have been taken: polishing R_a = 0.03 μm, grinding R_a = 0.10 μm and polishing R_a = 0.15 μm. The initiation and growth of surface fatigue damage have been studied by Scanning Electron Microscopy and spectroscopy techniques.
The kind of pre treatment has a strong influence on surface fatigue life time. For polished substrates (R_a = 0.03 μm) best results have been obtained for TiCN. For ground substrates (R_a = 0.10 μm) best results have been obtained for TiAlN/TiN. The damage mechanisms of TiN and WC/C are completely different.

1. INTRODUCTION

PVD coatings on steel are deposited on steel to enhance performance, and indeed PVD coatings show general good performance under sliding contact conditions. For many applications a good adherence of a coating to a substrate is required, also under fluctuating high contact stresses, to achieve economically interesting technical life times. If the contact stresses are high enough plastic deformation of the steel substrate will occur and a high stress level at the interface of PVD layer and steel is inevitable. In industrial practise, e.g. in tools for sheet metal forming, plastic deformation of steel has to be avoided, but also with elastic deformation of the substrate a relatively high stress level at the interface will be found. In industrial practise most plastic deformation is avoided by a high substrate hardness and in this respect a substrate hardness of at least 60 HRC is chosen. The detrimental effect of a relatively soft substrate, e.g. about 50 HRC, is widely known. The beneficial effect of a higher substrate hardness, tool steel with a hardness up to 67 HRC, will be reported elsewhere.

In many tribological contacts micro cracks start at the interface or in the bottom section of PVD coatings. Usually compressive stresses are present in PVD layers, however tensile stresses may become dominant especially just outside the contact area. After initiation and growth of these cracks parts of the PVD coating will easily break away, both interfacial adhesive failures and cohesive failures are observed.
Rolling contact fatigue (RCF) experiments have been performed to study the resistance of PVD coated tool steel against surface fatigue. The influence of pre treatment and roughness of the substrate is studied by an experimental tribological approach with only lubricated experiments. Microscopical inspection and analysing techniques have been used to reveal the damage mechanisms.

2. RCF EXPERMENTS

RCF experiments have been performed with a modified pin on ring test apparatus [1]. The test equipment is schematically depicted in figure 1. All tests were done under lubricated conditions, a mineral oil (BP Energol CS 68) without additives has been used. The oil is also a coolant keeping the temperature at a level between 20°C and 30 °C.

Table 1 Overview of test rings; two rings for each combination of substrate and coating

Hardness (HRC)	60	60	60	50
Finish	polished	polished	ground	polished
Roughness (R_a in μm)				
Before PVD	0.03	0.15	0.10	0.03
After PVD in axial direction	0.09	0.20	0.09-0.21	0.10
in tangential direction	0.15-0.27	0.25	0.14-0.24	-
PVD Surface Treatment	TiN	TiN	TiN	TiN
	TiAlN/TiN	-	TiAlN/TiN	-
	TiCN	-	TiCN	-
	WC/C	-	WC/C	-
	not coated	not coated	-	-

Contact was achieved by pressing a ball made of hard metal GT 10 and with a diameter of 16 mm, against the outer diameter of the ring under a known normal load. This load was applied through a pneumatic pressure unit ranging from 0.4 till 1.2 kN, the corresponding maximum contact stresses are in the range 3.1GPa till 4.1 GPa for uncoated rings and 4.2 GPa till 5.4 GPa for PVD coated rings.
The ball rotates in a bronze socket along a fixed axis parallel to the axis of rotation of the ring, resulting in a pure rolling contact of ball and ring. The rings have a diameter of 60 mm and a width of 13 mm. A ring rotates at a speed of 500 revolutions per minute, the contact speed is 1.6 m/s.

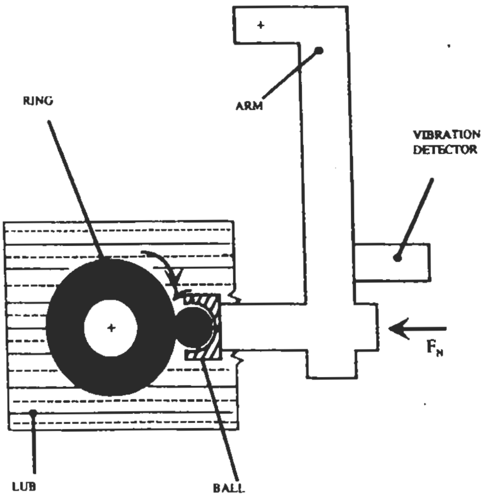

Figure 1. RCF test apparatus schematically

A vibration detector is mounted on the lever arm detecting the surface deterioration as a result of surface fatigue. The fatigue life time is reached when 1% of the contact path on the ring outer diameter shows delamination by visual inspection. The increase in vibration level corresponding with 1% delamination has been found to be in the range 15% - 20 %. A test is stopped automatically when the selected vibration level has been reached.
As hard metal has a very high resistance against surface fatigue, a ball usually survives many tests. At the start of each test it is verified that an undamaged ball is used. It is possible to perform about five tests per ring by shifting the ring in the axial direction between tests.

3. MATERIALS

Rings were made from tool steel Sverker 21 (12 % Cr steel, AISI D2, WN 1.2379). Most rings are heat treated and tempered at 520 °C to obtain about 60 HRC. All rings have been treated in one batch. Two rings have been tempered at 600 °C to obtain a hardness of 50 HRC.
After the heat treatment the surfaces were finished in different ways (Table 1):

- polished to an R_a value of 0.03 μm or 0.15 μm
- ground to an R_a value of 0.10 μm

Table 2 Hardness of rings after PVD treatment

PVD layer	Hardness in HRC	Standard deviation	Micro hardness
TiN	57.0	2.0	2300
TiAlN/TiN	54.4	2.8	3000
TiCN	59.0	0.7	3000
WC/C	57.2	2.0	1000
No PVD	60.6	0.4	-

4. EXPERIMENTAL RESULTS

4.1. TiN coatings

Figure 2 shows experimental results for TiN on steel with an original hardness of 60 HRC. Some trends can be observed:

- Especially at lower contact stresses best results are obtained on fine polished (R_a=0.03 μm) specimen. At the highest contact stress the results show a lot of scatter.
- The results obtained from steel with a hardness of 60 HRC have a much larger standard deviation than those obtained from 50 HRC specimen. In section 5 we will describe the difference in crack growth between a softer (50 HRC) and a hard (60 HRC) substrate.

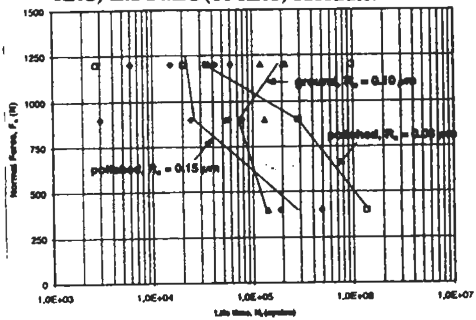

Figure 2. RCF results for TiN on steel with hardness 60 HRC.

4.2. Other coatings

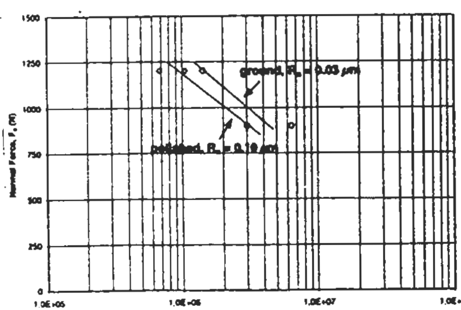

Figure 3 RCF results for TiAlN/TiN coatings. Ground specimen (R_a = 0.10 μm) show a slightly longer fatigue life than polished specimen (R_a = 0.03 μm). Substrate roughness has minor influence because of a relatively high roughness due to Al-rich defects in the PVD layer.

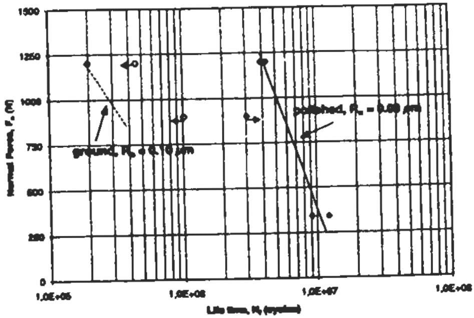

Figure 4 RCF results for TiCN coatings. Polished specimen (R_a = 0.03μm) have a much longer fatigue life time than ground ones (R_a = 0.10 μm).

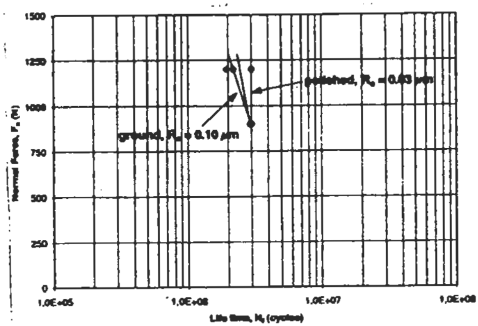

Figure 5 RCF results for WC/C coatings. Polished specimen (R_a = 0.03 μm) and ground specimen (R_a = 0.10 μm) have the same fatigue life times.

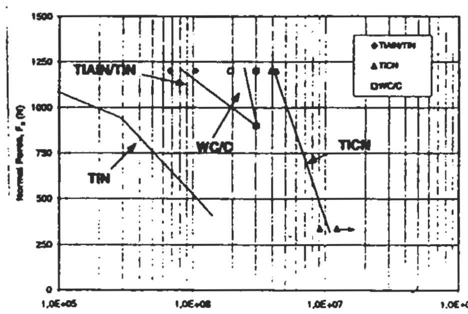

Figure 6. Comparison of measured surface fatigue properties on polished (R_a = 0.03 μm) substrates with a hardness of 60 HRC. Best results are obtained for TiCN coatings.

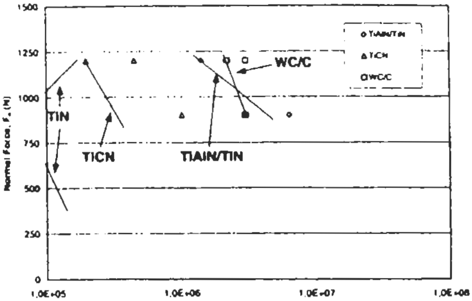

Figure 7. Comparison of measured surface fatigue properties on ground ($R_a = 0.10$ µm) substrates with a hardness of 60 HRC. Good results are obtained for WC/C coatings and for TiAlN/TiN coatings.

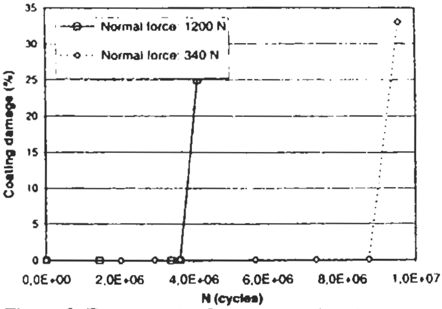

Figure 8. Fast growth of visible coating damage after incubation period (TiCN polished $R_a = 0.03$ µm).

5. DAMAGE MECHANISMS

Visual inspection during a fatigue test combined with registration of vibration level is used to visualise the growth rate of fatigue damage. The vibration signal corresponds with visible coating surface damage. An example of the fatigue damage growth rate of TiCN is given in figure 8. It is found that visual or detectable damage does not start during an incubation period, after this period damage grows very fast. It is observed that at the end of the incubation time a relatively large part, typical size 50 µm diameter, of the coating breaks away and that the damaged area grows by chips breaking away; typical sizes 4 µm width and 15 µm to 75 µm long. The area grows only in the rolling direction (Figures 9a and 9b). Such a mechanism is also described in reference 3.

By continued rolling more of these long delaminated sites are found besides one another till the whole contact area on the outer diameter of a ring is filled. TiN, TiAlN/TiN and TiN show this behaviour, whereas WC/C shows a completely different growth mechanism.

For WC/C coated specimen the visible fatigue damage starts immediately after the start of a test and grows slowly. Cross sections show that damage is caused by cohesive failure of these layers, as depicted in figure 10. Since the compressive stresses in a WC/C layer are relatively low these failures are probably due to tensile stresses. Small chips broken off are found elsewhere in the contact area on top of the WC/C layer on the outer diameter of a ring. A WC/C layer consists of a chromium columnar interlayer, an intermultilayer of WC and carbon with chromium carbides, an amorphous WC layer and a WC/C multilayer, more details can be found in [4].

Figure 9a
SEM micrograph of the edge of growing surface fatigue failure in a PVD - TiN layer tested with a normal force of 400 N giving a maximum contact pressure: 4.2 GPa. The failure grows in the rolling direction.

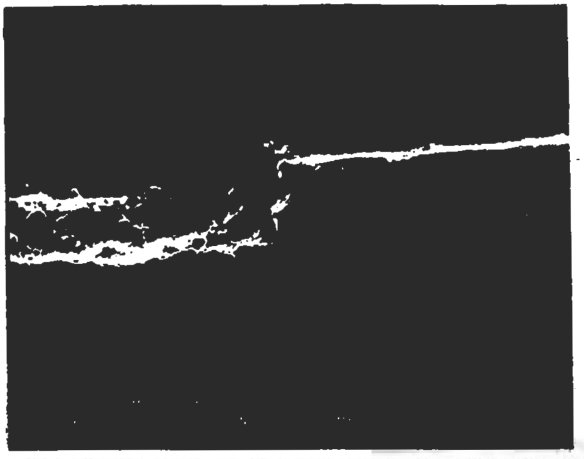

Figure 9b. Cross section of TiN showing the same growth mechanism as depicted above. This specimen has been tested with a normal force of 1200 N giving a maximum contact pressure: 5.4 GPa. Note that the crack visible in the bottom section of the PVD layer grows perpendicular towards the surface. However the whole layer delaminates.

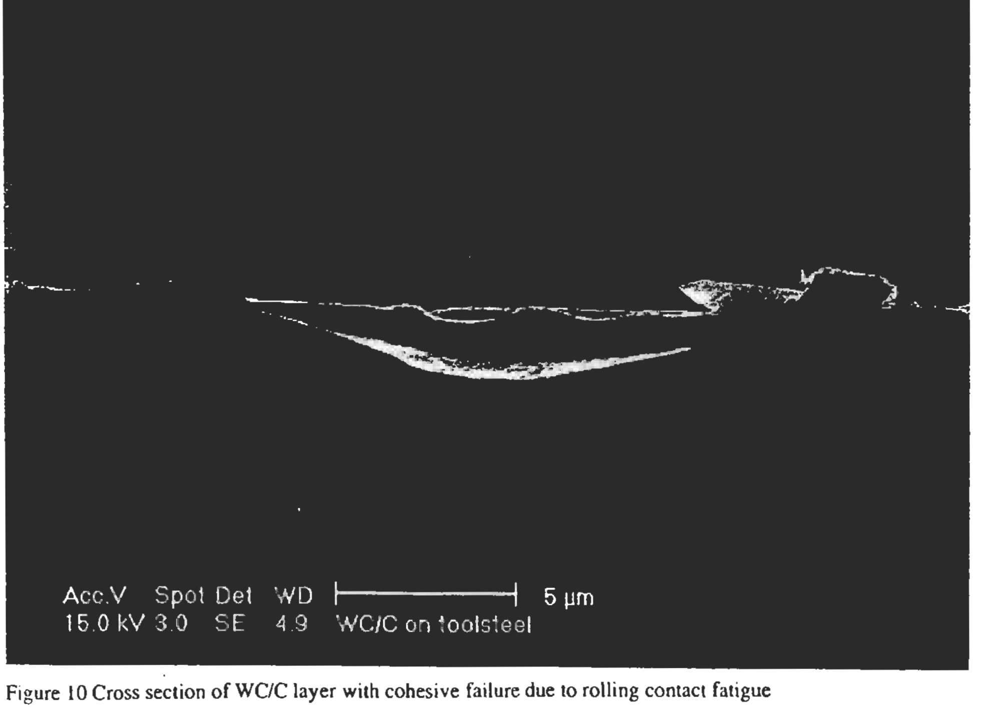

Figure 10 Cross section of WC/C layer with cohesive failure due to rolling contact fatigue

With respect to TiAlN/TiN layers it is of importance to realise that these coatings have the highest roughness due to Al rich defects in the coatings. In addition they have the lowest substrate hardness after the PVD treatment. Both roughness and hardness probably can be improved thereby improving the surface fatigue resistance.

When the substrate hardness is about 50 HRC strong plastic deformation of the substrate will occur. Cracks initiate in the substrate and grow towards the interface between PVD coating and substrate. Where a crack meets the interface delamination may occur. When the adhesion is very well cracks perpendicular to the surface will grow with only locally some delamination.

6. SUMMARY

The surface fatigue properties of PVD coatings: TiN, TiAlN/TiN, TiCN and WC/C, on hardened tool steel have been measured under lubricated rolling contact conditions. These coatings have thickness' in the range 3 μm – 5 μm. The RCF experiments have been done in order to measure the adhesive strength of these coatings on steel under fluctuating contact stresses. Initiation and growth of damage have been studied by visual inspection, registration of vibration levels and microscopical inspection of tested specimen.

- TiN coatings on polished (R_a= 0.10 μm) rings reveal slightly longer fatigue life's than TiN coatings on less fine polished (R_a= 0.15μm) rings.
- For TiCN coatings polished steel (R_a = 0.03 μm) is a much better substrate than ground (R_a = 0.10 μm) steel.
- For TiAlN/TiN coatings a small effect in the opposite direction has been measured, ground rings (R_a = 0.10 μm) give slightly better results than polished rings (R_a = 0.03 μm). This is at least partly caused by a relatively high roughness due to defects in the layer.
- For WC/C coatings the applied pre treatments gave no difference in surface fatigue properties.
- For polished (R_a = 0.03 μm) specimen the ranking for best surface fatigue resistance is: TiCN > WC/C > TiAlN/TiN > TiN.
- For ground (R_a =0.10μm) specimen the ranking for best surface fatigue resistance is: TiAlN/TiN and WC/C > TiCN > TiN.
- The growth of fatigue damage in TiN and TiCN starts after an incubation period and grows fast after initiation.
- A WC/C layer looses small chips immediately after the start of fatigue loading, however the growth rate is relatively slow. The properties of WC/C can be compared with solid lubricants.

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