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ROLLING/SLIDING CONTACT FAILURE OBSERVATIONS OF SOME CARBON COATED BEARING STEELS (I)

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ABSTRACT

This paper investigates the performance of amorphous carbon (CotI) coatings, tetrahedral amorphous carbon (CotII), hydrogen free coatings, and chromium plus tungsten-doped hydrogenated carbon (CotIII) coatings deposited on hardened and tempered 100Cr6 steel rollers. The study was carried out under rolling/sliding lubricated conditions against uncoated 100Cr6 steel counterface washers with a constant load and spindle speed. The surfaces were analyzed using light optical microscopy, scanning electron microscopy (SEM), energy dispersive X-ray analysis (EDX), profilometry, and scratch testing prior to, and after rolling contact fatigue (RCF) tests.

In the case of CotI, the results showed that the durability (the running time prior to detection of surface failure) of the coatings was inversely proportional to the contact pressure.The durability, failure mode, and friction coefficient of the three coatings (under similar circumstances) varied significantly which is linked to the coating properties and the interaction between the coatings and both the lubricant and the counterface.

Keywords: Carbon, Steels, Coatings etc.

1. INTRODUCTION

Different types of new wear resistant carbon based coatings for combined sliding and rolling contact are currently being developed to protect the surfaces of automobile engine components.The role of these coatings was not only to protect contact surfaces but also to replace the extreme pressure (EP) lubricants that have been used, as they contain toxic additives. Another reason is to overcome a certain number of limitations, notably the high level of friction in EP components. Due to their combined low friction and wear characteristics, and also to their inertness to corrosive environments, carbon coatings are amongst the most popularly used protective coatings [1][2]. Not only are they used on tools, carbon coatings currently also account for over 70% of all component

coatings.These types of hard coatings have not been extensively studied under rolling/sliding contact conditions as found for example in the cam/cam follower contact situation. In this study periodic examinations were carried out to capture the failure initiation time, and evaluate (in some situations) the progress of wear (failure).

2. TEST MATERIAL & METHODS

2.1 Materials & Characterization

The steel rollers and washers were obtained from standard roller thrust bearings (product code 81111) manufactured by INA/Germany. All rollers were 8 mm in length and 6 mm in diameter and were made from fully martensitic 100Cr6 steel (1.0% C, 1.5% Cr bearing steel similar to SAE52100), with a nominal Vickers hardness of 760. A number of rollers (extracted from the thrust bearings) were coated with CotI and CotII (Fraunhofer Institut für Werkstoff-und Strahltechnik (IWS)) and CotIII (Hauzer Techno Coating). The thickness of the coatings was determined from cross and taper sections of some of the coated rollers, using light optical microscopy, SEM, and Wyko optical profilometry. Coating microhardness was determined using a Shimadzu HMV 2000. The method of Vingsbo et al. [3] was used to subtract the influence of substrate hardness. Nominal coating thickness and hardness data are given in Table 1.

2.2 Rolling Contest Test

The CotI, CotII, and CotIII coated 100Cr6 rollers were tested in a plain mineral base oil, FVA-3. A proportion of the CotI coated rollers were also tested in a fully formulated oil (Selena SAE 10W40). Coated steel rollers were tested using two identical rolling contact fatigue test rigs. Most coated rollers were tested using a maximum Hertz contact pressure of 1540 MPa. The CotI coated rollers were also tested at maximum Hertz contact pressures of 943 MPa and 1222 MPa respectively. Table 2 presents the basic set-up conditions while the schematic of the test rig head is shown in Fig 1. To detect the onset of any pitting or coating delamination, two accelerometers were used to measure the vibration from the test rig. Friction force was measured on each machine using a HBM S2, 50N strain gauge transducer. Data from these were used to determined the friction coefficient.

3. RESULTS

The friction coefficient, average durability of the three coated (CotI, CotII, and Cr+ CotIII) rollers, and wear rate of the counterface washer (determined at 1540 MPa) are summarized in Fig 2. The most durable rollers were those coated with CotIII, where lifetimes were about 10 and 50 times respectively greater than the CotII and CotI coatings.

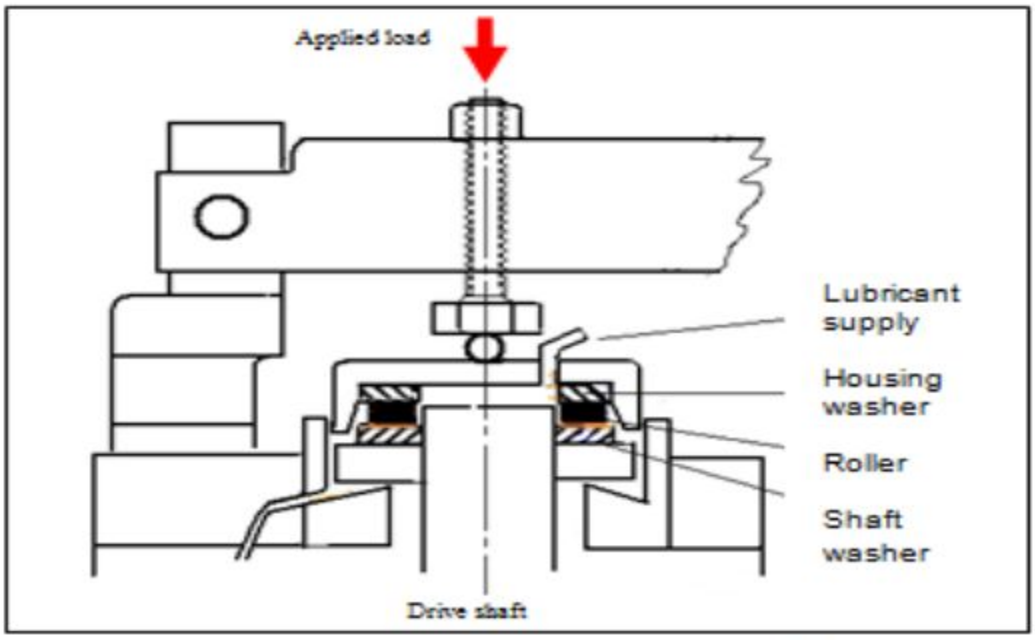

Fig 1 Main components of the test rig head

The durability of the CotI coated 100Cr6 rollers, tested at the same pressure in formulated oil, was about 50% greater compared to that when tested in the base oil. Fig 2a shows that the friction coefficients of CotII and CotIII are comparable while that of the CotI is lower. Fig 2c shows the washer tested against the CotI coated rollers had the greatest wear rate whilst the least was shown by the washer tested against the CotIII coated rollers. The relationship between the applied load and the coating durability of CotI coating in the formulated oil is shown in Fig 3. This resembles an S-N fatigue curve.

Fig 4 shows examples of the observed coating failures. Fig 4a and 4d show localised exfoliation of the CotI after 3 hrs testing and CotII after 15 hrs respectively whilst Fig 4b and 4c show polishing of the original surface asperities,microcracking and tearing of the CotIII.

Exfoliation/delamination failures were usually located close to the ends of the roller, where sliding dominated. Only about 20% of failures occurred at or close to the middle of the roller. The uncoated steel washers, tested against the coated rollers, were slightly worn by polishing. This was detected by the change in surface roughness from optical interferometry (Wyko) measurements prior to, and after the RCF testing (Table 3).

Table 1 Coating Data

Coating type	Coating thickness (µm)	Load in variant hardness (kg/mm^2)
CotI	1.1	2415
CotII	2.0	3095
CotIII	1.0	1800

4. DISCUSSION

Polishing (micro-abrasion) wear always took place during RCF testing regardless of the contact pair. While this was the dominant wear mechanism for the uncoated washers and the CotIII coated rollers, exfoliation/delamination predominated for the CotI and CotII coated rollers. Stress concentrations at the peak asperities of the CotI and CotII coating may have been responsible for initiating exfoliation failures [4]. The sp3/sp2 ratio was low for the CotI coating (30%), but higher for the CotII coating (80%). The sp2 regions are weakly bound by van der Waals forces, while sp3 regions are more strongly covalently bonded [5]. Accordingly, fracture initiation would be easier in the former material and this may explain the slightly greater durability of the CotII coated rollers. However, the fatigue fracture toughness of the coating /substrate interface is also of great importance. The CotIIIcoated rollers showed no delamination which indicates a high coating/substrate interface fracture toughness. The magnitude of the stress concentration at the tip of any interface crack would be proportional to the maximum Hertzian stress and the fatigue crack length would be proportional to the number of test cycles. Accordingly, a classical fatigue type S-N behaviour takes place (Fig 3). The durability of CotI coating was slightly improved (Fig 2b) when tested in the formulated oil and the apparent wear rate was lowered (Fig 2c), i.e., either the initiation and/or the growth of the fatigue cracks responsible for causing coating delamination was slightly curtailed by this type of oil. This effect may arise from the formation of antiwear tribo-films: these can minimise surface stresses for a given contact force [6]. Formulated oils containing ZDDP (anti-wear) and MoDTP additives decompose to form micrometer sized "pads" of ZnS, FeS and Zn polyphosphides. These restrict direct contact between the roller and washer surfaces and can, in principle, limit delamination coating failures [7].

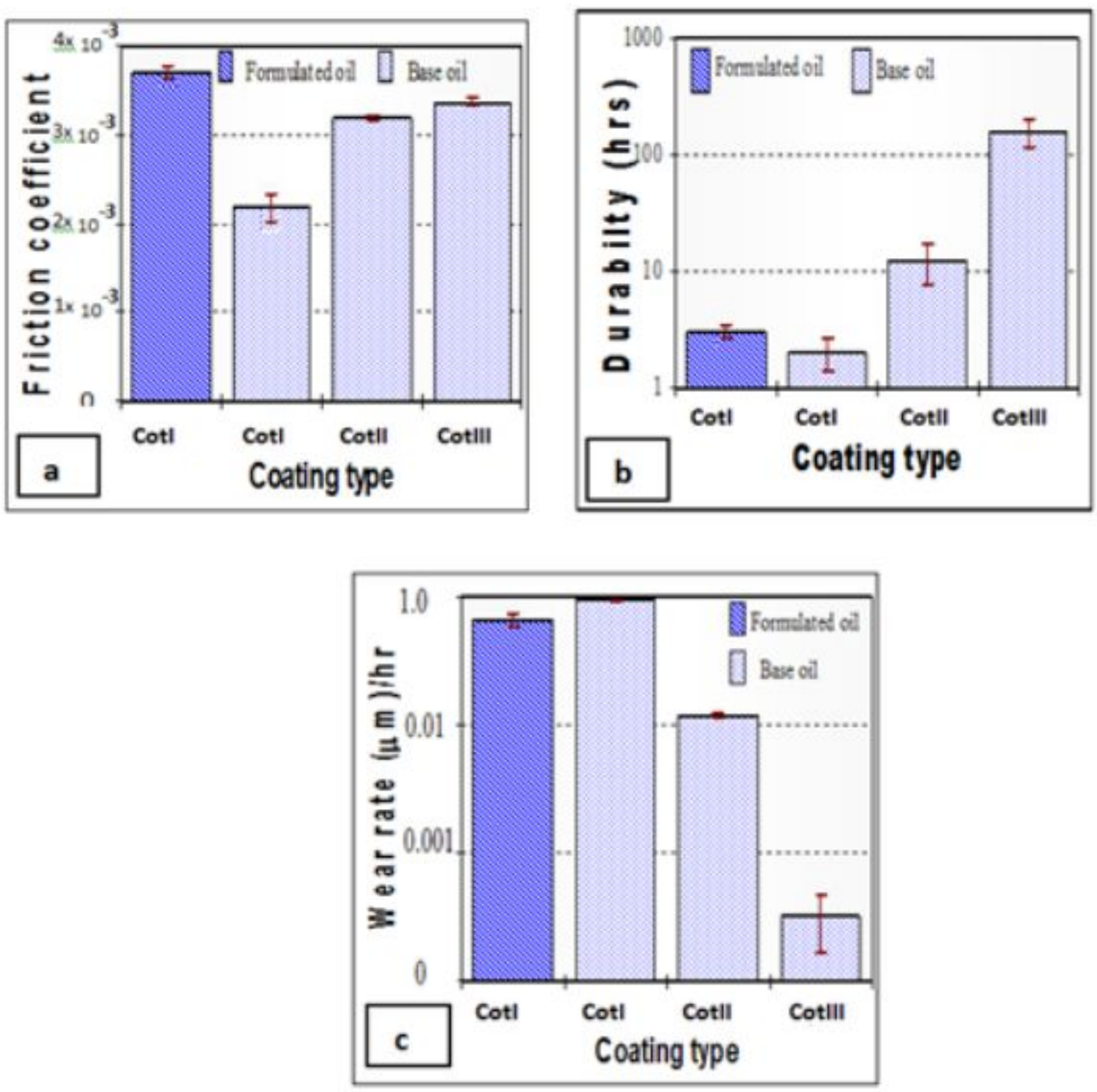

Fig 2 - (a) Friction coefficient data; (b) Mean durability of coated rollers at 1540 MPa; and (c) Mean wear rate / running time for steel counterface washers against various coated rollers.

Table 2 Basic set up conditions

Substrate and counterface material	100 Cr6 Steel
Roller diameter, length (mm)	3, 8
Contact pressure range (MPa)	943-1540
Rotation speed (r/min)	1450
Lubricants	Base, formulated (10 W 40)
Roller speed, sliding speed (m/s)	25, 0.25

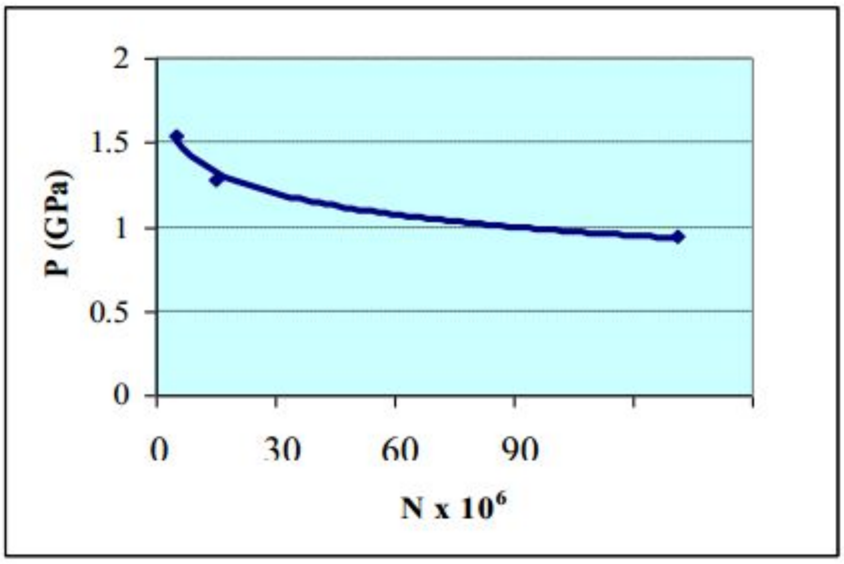

Fig 3 The relationship between the Hertzian pressure (P) and the no.

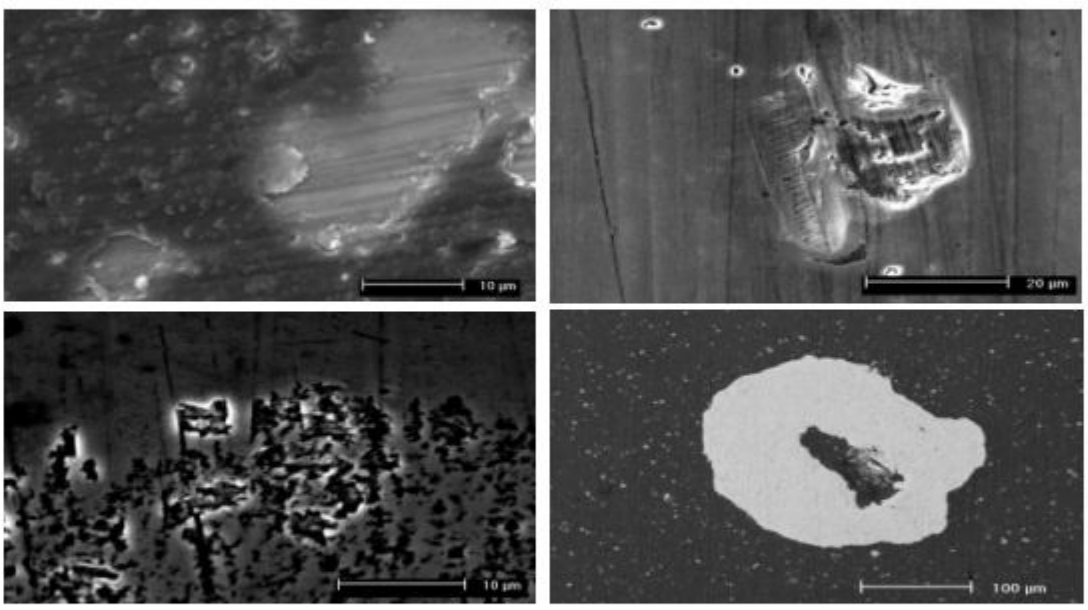

Fig 4 – (a) Localised exfoliation of CotI (after 3 hrs), (b) Polishing, microcracking and tearing of CotIII (after 150 hrs), (c) Polishing and micro-pitting of CotIII (after 150 hrs) and (d) Delamination of CotII (after 15 hrs)

Table 3 Surface roughness data for uncoated steel washers prior to and after RCF test against indicated coated rollers

Coating counterpart	Washer Ra prior to RCF test (µm)	Washer Ra after RCF test (µm)
CotI	0.1348	0.0105
CotII	0.1066	0.0105
CotIII	0.1636	0.1217

5. CONCLUSION

Lubricated rolling/sliding contact tests were carried out on a series of carbon coated 100Cr6 steel rollers that emulate cam/cam follower contacts in automobile engines. At 1.54 GPa normal contact pressure, the durability of CotIII > CotII > CotI. The CotI and CotII coatings failed by delamination at the coating/substrate interface which was probably of a fatigue character. Failure of the CotIII coatings was determined by micro-abrasion (polishing) wear and no delamination took place.

6. REFERENCES

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