

The Mechanism of Failure With and Without Titanium Nitride Coating in Roller Tests

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American Gear Manufacturers Association



TECHNICAL PAPER

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ABSTRACT:

To clarify the effect of Titanium Nitride (TiN) coatings on the failure resistance and frictional characteristic and compare this effect with that produced by the heat treated coatings, two roller tests have been made and the stress resulting from the combination of the Hertzian stress field and frictional force field on and below the contacting surface as well as the flash temperature rise were calculated. The failure resistance of the TiN-coated roller pair was greater than that of the heat treated roller pair. The mechanism of failure resistance can be explained by the shearing stress (Hertzian stress + frictional force) acting on the contact surface. This stress modifies the structure in the vicinity below the TiN layer which is then sheared in the wear track direction.

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THE MECHANISM OF FAILURE WITH AND WITHOUT TITANIUM NITRIDE COATING IN ROLLER TESTS

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1 INTRODUCTION

To increase wear resistance of cutting tools hard coatings such as titanium carbide, titanium nitride and aluminium oxide are applied to the surface of tools. These coatings are also widely applied to wear resistant parts and mechanical components. There are a great number of reports in which the scuffing resistance of gears and mechanism of scoring was investigated using a two-roller machine. Scoring resistance of TiC- and TiN coated gears was investigated by Terauchi et al. [1] who found out that the scuffing resistance of the coated roller pairs was higher than that of the uncoated roller pair. The mechanism of seizure in a two-roller test was investigated by Nadano et al. [2]. He has found that a part of the wear track on the upper roller was fractured due to shearing stress at the position where the hardness of the roller was minimum, and adhered to the contacting surface of the lower roller.

In this paper roller pairs were examined in the incipient stage of failure. Observations of microhardness of the structure at the failed portion of the heat treated- and TiN- layer in two-roller tests, and on the basis of calculation of the stress on and below the surface of the roller, the mechanism of the failure of the TiN-layer in comparison with the fracture of the heat treated

2. TEST SPECIMENS AND EXPERIMENTAL METHOD

The drawings of the cylindrical rollers used in the two-roller test are shown in Figure 1. The rollers were

made of X155 Cr VMo 12-1 (Č 4850) and S6-5-2 (Č 7680) tool steels. The combination of roller pairs, heat treatment and coating treatment are shown in Table 1.

The TiN coating of a thickness of 2 to 4 µm was produced by the physical vapour deposition (PVD) process. The thermal properties and hardness of the material of the rollers and the coatings are shown in Table 2.

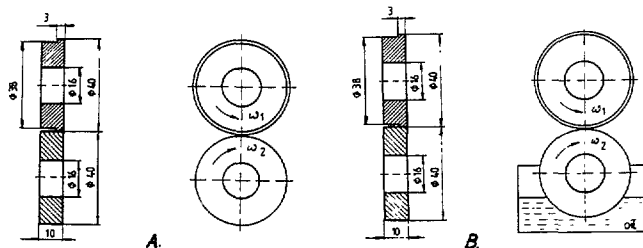


Figure 1. The profile and dimensions of the rollers

Material DIN, JUS AISI	Roller pair	Upper roller		Lower roller	
		Heat treatment	coating	Heat treatment	coating
C.4850 X155CrVMo 12-1 D2	Type A	980 °C, oil, 12min 500 °C, air, 2h 500 °C, air, 2h	/	980 °C, oil, 12min 500 °C, air, 2h 500 °C, air, 2h	/
	Type B	/	TiN	/	TiN
C.7680 S6-5-2 M2	Type C	1215 °C, oil, 2min 600 °C, air, 1h 600 °C, air, 1h	/	1215 °C, oil, 2min 600 °C, air, 1h 600 °C, air, 1h	/
	Type D	/	TiN	/	TiN

Table 1 Combination of roller pairs, heat treatment and coating treatment

The surface roughness of the rollers in the axial direction is shown in Table 3. The surface roughness of the coated rollers was similar to that before the coating was applied. The peripheral velocities, the specific sliding and other test conditions of the two-roller test are shown in Table 4.

Properties	Material			
	X155 CrVMo12-1 (C.4850)		S6-5-2 (C.7680)	
	Treated Type A	(Untreated)+TiN Type B	Treated Type C	(Untreated)+TiN Type D
Vickers microhardness (HV)	683	(230) 2000	657	(230) 2000
Thermal conductivity K(W/mk)	28	19	24	19
Thermal diffusivity k(m ² /s)	6.62x10 ⁻⁶	5.3x10 ⁻⁶	6.62x10 ⁻⁶	5.3x10 ⁻⁶
Specific heat, c(kJ/kgK)	0.460	0.700	0.460	0.700
Density, (kg/m ³)	7750	5440	7750	5440

Table 2 Hardness and thermal properties of roller and coating

Surface roughness [μm]	Roller pair				
		Type A	Type B	Type C	Type D
Befor	Ra	0.5	1.52	1.07	1.73
Coating	Rmax	4.97	7.81	7.21	7.71
After Unlubricated Test	Ra	0.24	0.14	0.46	0.28
	Rmax	1.64	2.55	3.38	4.53
After Lubricated Test	Ra	0.20	0.14	0.36	0.34
	Rmax	2.02	3.55	2.92	6.3

Table 3. Surface roughness before and after the roller test

Conditions	Upper roller	Lower roller
Peripheral velocity, W (m/s)	0.42	0.38
Specific sliding, 0.095		-0.105
Radius, R (mm)	20	20
Width, b (mm)	3	10
Normal Load, F (N)	500	500
Initial oil temperature (K)	293±2	293±2

Table 4 Specification of the test conditions

The test conditions were kept constant during the test. The test was carried out using a two - roller machine. The rollers were lubricated with describe additives EPOL SP 150. They prevent scuffing a straight mineral oil with additives, with kinematic viscosities of 214 10⁻⁶ m²/s at 313 K and 17.2 10⁻⁶ m²/s at 373 K. The roller tests were carried out with unforced lubrication as shown in Figure 1. The oil temperature was controlled to +/- 4 K by a thermostat.

3. RESULTS AND DISCUSSION

3.1. Failure resistance

Figure 2 shows the calculated values of the flash temperature rise and the maximum Hertzian stress P_{max} at the start and at the incipient stage of failure, unlubricated and incipient stage when lubricated of the roller pairs tested. The flash temperature rise was calculated by the equation given in reference /3/, and the value of the coefficient of friction that was measured just before failure occurred and at the beginning of the roller pair tests. The Hertzian stress was constant during the tests. The flash temperature rise of the roller pairs Type B and Type D unlubricated was approximately 370 to 430 K higher than that Type A and Type C.

while the temperature rise of the roller pairs Type B and Type D lubricated was approximately by 70-95 K higher than that in Type A and Type C. The minimum oil film thickness calculated by Dowson's equation /4/ in a line contact on the roller pairs was approximately 0.7 X 10⁻⁴ mm. As the value defined by Wellauer /5/, The ratio of the film thickness to combined surface roughness as defined by Wellauer /5/ was from 0.095 to 0.248. The tests were run at very low lambda value perhaps almost metallic contact.

3.1.1. Lubricated friction

The relationship between the coefficient of friction and the wear length is shown in Figure 3. The measurement of the coefficient of friction was carried out twice for each roller pair. Since the two values were similar, their mean value is shown.

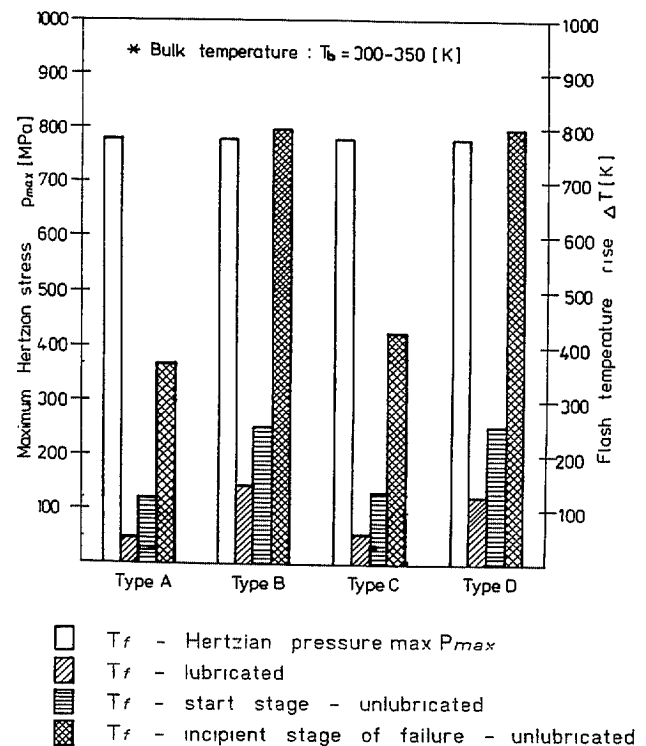


Figure 2 Calculated surface temperature rise and maximum Hertzian stress at the incipient stage of failure and at the initial stage

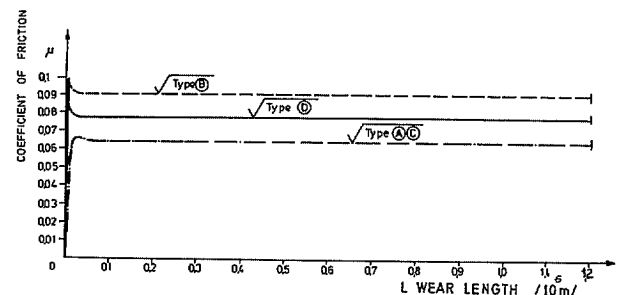


Figure 3 Relationship between coefficient of friction and wear length - lubricated conditions

For all roller pairs, the coefficient of friction just after the beginning of the test had a maximum value. After that, it decreased to a constant value with increasing wear length. The coefficient of friction of the roller pairs Type A and C was 0.065, that of the roller pair Type D was 0.078 and that of the roller pair Type B was highest 0.09.

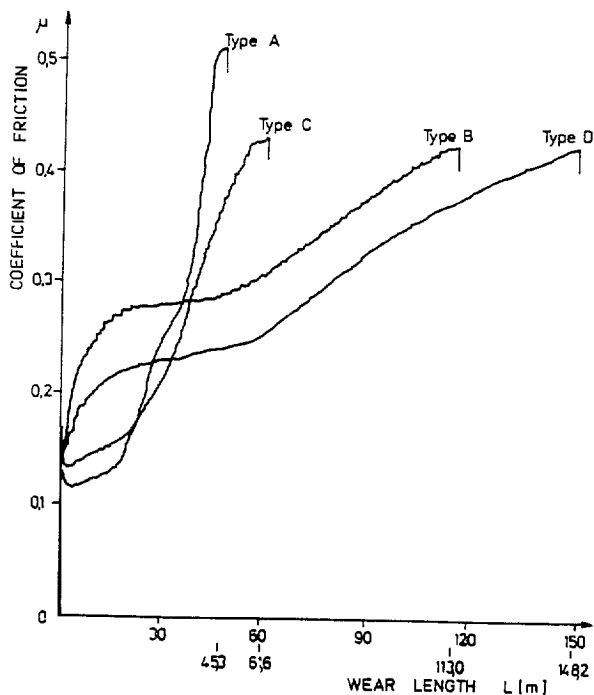


Figure 4. Relationship between coefficient of friction and unlubricated conditions for four roller pairs

The coefficient of friction varied with the difference in the base material and coating on the roller. For all the roller pairs it appeared that the surface was uniformly torn out due to frictional forces and wear; however, the contacting surfaces became smoother as shown in Table 3.

3.1.2. Unlubricated tests

As the failure resistance of the coated and uncoated rollers could not be estimated from the test results obtained under lubrication, the failure test was carried out unlubricated. The testing was stopped when failure was observed. The initial friction coefficients were about 0.12 to 0.16 respectively. The relationship between the coefficient of friction and the wear length is shown in Figure 4.

Figure 5 shows the running time until failure occurred. The test was carried out twice for each roller pair, and the mean value out of two measured values is shown. The life of the coatings of the roller pairs Type B and D was longer than that of roller pairs Type A and C.

4 OBSERVATION OF FAILED AREAS

4.1. Lubricated tests

Figures 6 A B show a micrograph of the wear track of the rollers Type A and C after a $1.2 \cdot 10^6$ m.

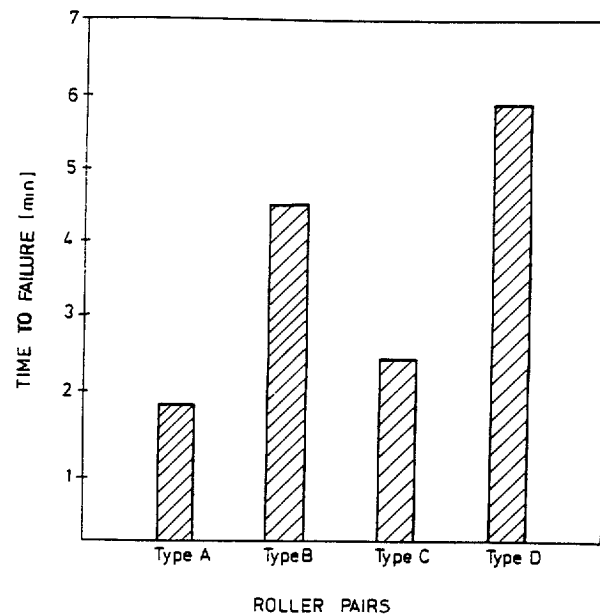
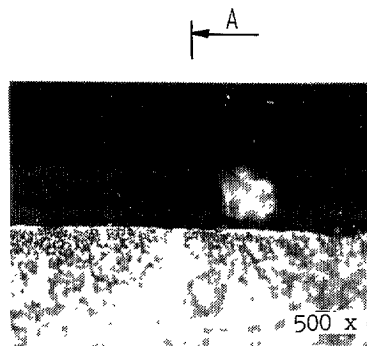


Figure 5 Time to failure of unlubricated roller pairs

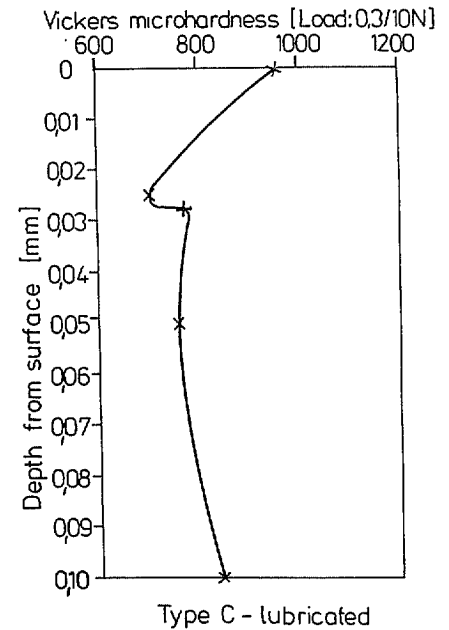
wear length. The surface layer of the roller Type C was slightly more sheared in the direction of frictional force. Along the contact surface and in the vicinity of the surface there are distinct modifications of microstructure induced by shear stresses and temperature. This can be confirmed by the fact that the hardness is considerably higher than that in the subsurfaces. Figure 6 B shows the change in Vickers microhardness with depths measured along the line A - A, probably caused by work-hardening due to the action of compressive stress, frictional force and cooling with lubricating oil. Figure 7 A shows a micrograph of the wear track of the roller Type B after failure at about $1.2 \cdot 10^6$ m. An undulation was observed in the circumferential direction of the roller and the TiN surface layer was fatigue-damaged in the direction of the frictional force. Figure 7 B shows a micrograph of the section plane cut in axial direction of the roller and the distribution of Vickers microhardness measured along the line A-A. From this micrograph it can be seen that the metal in the vicinity below the TiN layer was distinctly deformed. The hardness in the vicinity of the boundary of the TiN layer was the same as that before the tests. The TiN layer had a larger elasticity modulus than the base material, and that the compressive, shear and thermal stresses cause a much larger deformation in the base material in the vicinity of the TiN layer than that in the TiN layer. On the other hand the surface temperature was lower than that used for heat treatment.



ACTING DIRECTION
OF FRICTIONAL FORCE

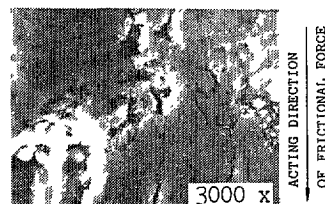
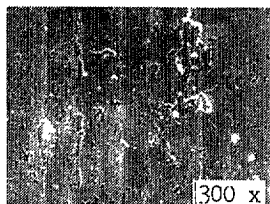


(B) MICROPHOTOGRAPH OF
SECTIONAL PLANE CUT IN
THE AXIAL DIRECTION OF
ROLLER AND DISTRIBUTION
OF HARDNESS ALONG
LINE A-A

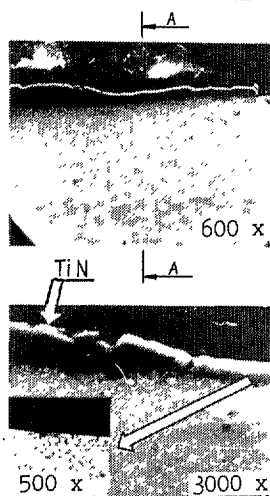


(A) WEAR TRACK AFTER
FAILURE OCCURED

Figure 6 Micrographs and sub-surface hardness of the wear track type A. C no coating



(A) WEAR TRACK AFTER FAILURE OCCURED



(B) MICROPHOTOGRAPH OF SECTIONAL PLANE
CUT IN THE AXIAL DIRECTION OF ROLLER AND
DISTRIBUTION OF HARDNESS ALONG LINE A-A

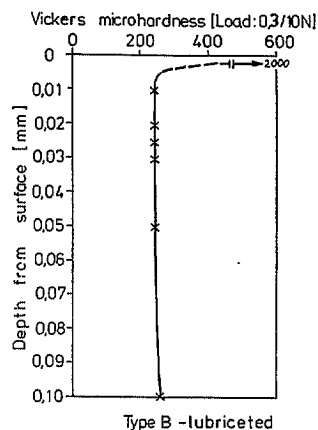
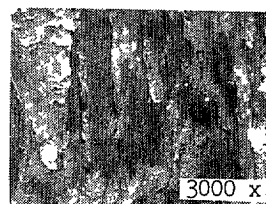
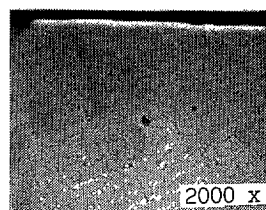


Figure 7 Microphotograph of failed portion of roller type B. with TiN coating



(A) WEAR TRACK AFTER
FAILURE OCCURED
(3000x)



(B) MICROPHOTOGRAPH OF SECTIONAL
PLANE CUT IN THE AXIAL
DIRECTION OF ROLLER AND
DISTRIBUTION OF HARDNESS
ALONG LINE A-A

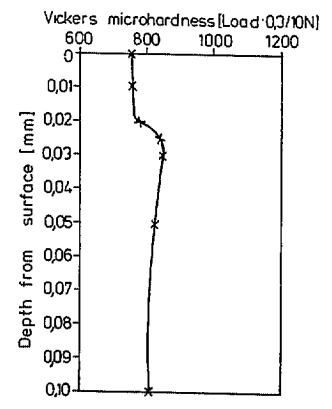


Figure 8 Microphotograph of failed portion of unlubricated roller type A no coating

The degree of surface fatigue damage of the TiN layer of the roller Type B was more substantial than that of the roller Type D

4.2. Unlubricated tests

Figure 8A shows a micrograph of the wear track of the roller Type A after failure unlubricated. An undulation was observed in the circumferential direction of the roller, and the surface layer was sheared in the direction of the frictional force. Figure 8B shows a micrograph of the sectional plane cut in the axial direction of the roller and the distribution of Vickers microhardness. Along the surface there are no signs of deformation. There was an approx. 1 μm thick layer of austenite. This confirms that the temperature was above the AC3 point which, according to the catalog, is 875°C. The austenite layer could not be separated from the wear track with a hammer impact. Therefore, the austenite layer was regarded as a structure affected by the actions of frictional force and frictional heat.

An undulation was observed in the circumferential direction of the roller Type C, and the surface layer of the roller was sheared in the direction of the frictional force. Along the tested surface there is an approx 1 μm thick layer of austenite. This layer was produced in the same way as that on roller pairs type A.

Figure 9, A,B shows a micrograph of the wear track and the sectional plane cut in the axial direction of the roller Type B after failure. Comparing the roller Type D with the roller Type B, the degree of surface fatigue damage by failure was higher than that found on the rollers pairs type D. Figure 9 B shows the distribution of Vickers microhardness which is the same as that before the tests. The mechanism of the failure of TiN-layer was slightly different appearance than that of the lubricated. The elastic deformation of the base material was larger than elastic deformation of the TiN-layer and larger than that of the heat-treated base material of the roller in the lubricated conditions

5. MECHANISM OF FAILURE

The frictional force acting on the contacting surface of the roller and the stress occurring on and below the surface were calculated by the author and shown in reference /6/.

As an example, the distribution of the equivalent stress σ_k , shear stress σ_{45° and reversed unidirectional stress σ_{zy} resulting from the combination of the Hertzian stress field and the frictional force field of the upper rollers are shown in Figure 10 and Figure 11 respectively. The value of the coefficient of friction is given from the measured value just before failure.

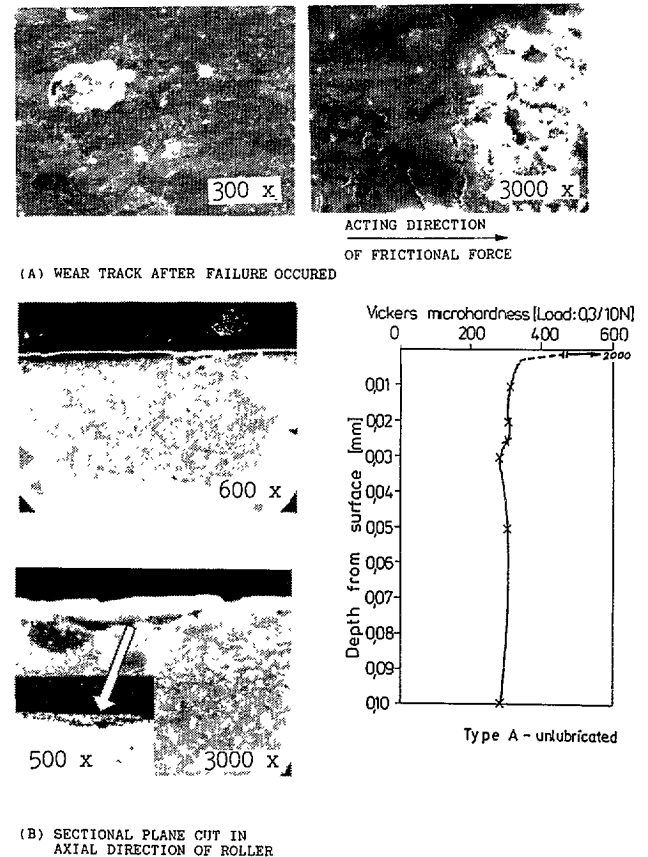


Figure 9 Micrograph of failure portion of the roller Type B with TiN coating

In Figures 10 and 11 the ordinate and abscissa indicate the position of the evaluated stress in terms of the parameters y and z

The patterns show that maximum value of the stresses σ_k , σ_{45° and σ_{zy} occurs below the contacting surface, and the profile of distribution of the stresses is approximately symmetrical to the origin for the roller pairs whose value of the coefficient of friction was under 0,1. On the contrary the profile of distribution of the stresses is not symmetrical to the origin for the roller whose value of the coefficient of friction was larger than 0,1. The maximum value of the stresses occurs on or below the surface, as shown Fig. 11.

Figures 12, 13 and 14 show the distribution of the maximum value of the equivalent stresses σ_k , the positive and negative components of the reversed shear stress σ the positive and negative components of the reversed shear stress σ_{zy} and shear stress σ_{45° for different values of friction coefficient.

Figure 11 shows the distribution of the equivalent stresses. The maximum value occurs at a depth " z " beneath the contact surface up to a coefficient of friction of 0,2. When the value of the coefficient of

friction is larger than 0.2 the maximum value of the equivalent stress occurs on the contact surface, Figure 12.

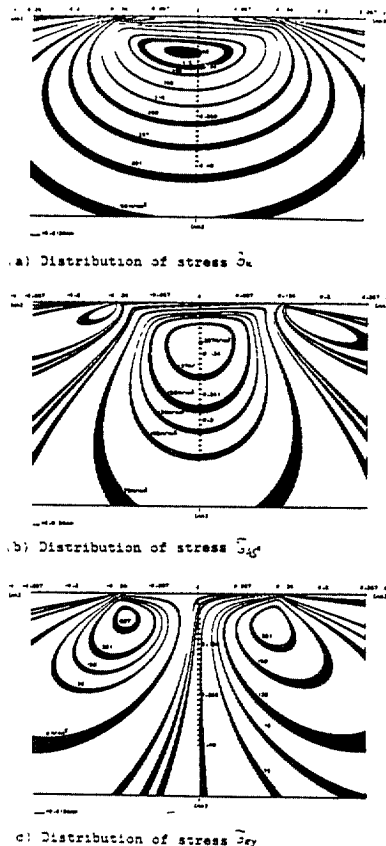


Figure 10 Distribution of resultant stress acting on the upper roller at the incipient stage of failure: coefficient of friction 0.065

The reversed shear stresses acting parallel to the plane of the contact surface and its maximum value occur at a depth "z" beneath the contact surface and are dependent on the coefficient of friction (Figure 14). The maximum shear stress value occurs at a constant depth "z" below the contact surface z_2 at an angle of 45° to the plane at the surface and is independent of the coefficient of friction. Figures 13. and 14

Figures 13 and 14 show the distribution of the maximum value of the positive and negative components of the reversed shearing stress and of the shearing stress acting on the upper rollers as a function of depth from surface. The same figures also present the values of the flow shearing stress for lubricated and dry friction conditions calculated from the micro hardness on the basis of equations published in the reference /8/. The reversed shearing stress acting at 5-10 μm below the contact surface of the roller type A and C is equal to the flow shearing stress with lubrication before the test

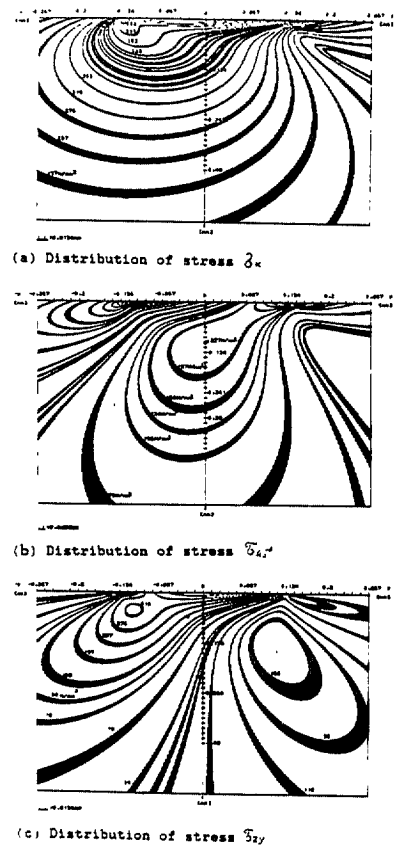


Figure 11 Distribution of resultant stress acting on the upper roller at the incipient stage of failure coefficient of friction 0.5

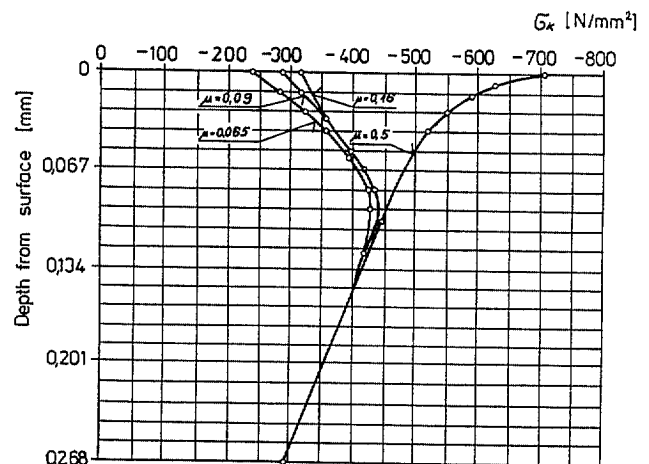


Figure 12. Distribution of equivalent stresses on and below the surface for different coefficient of friction, μ

Therefore this analysis showed that the surface layer of the roller type A and C is work-hardened and the mechanical properties of the layer increased. The surface layer of a thickness of about 15 μm cannot be fractured due to the shearing force acting on the surface of the roller. The reversed shearing stress in the same surface layer of the rollers type B and D is considerably higher than the flow shearing stress before and after the test with lubrication. Therefore, the layer which was deeper than 2-4 μm below the surface can be fractured due to the action of the shearing force on the contact surface of the roller with lubrication.

Under unlubricated conditions the reversed shearing stress below the TiN-layer of the roller pairs type A, B, C and D was considerably higher than the flow shearing stress before and after the tests. Therefore, the structure below the TiN layer can be fractured due to the action of the shearing force on the surface of the roller. As shown in Figures 6-9 the depth of the work-hardened layer and of the plastic deformation of the upper

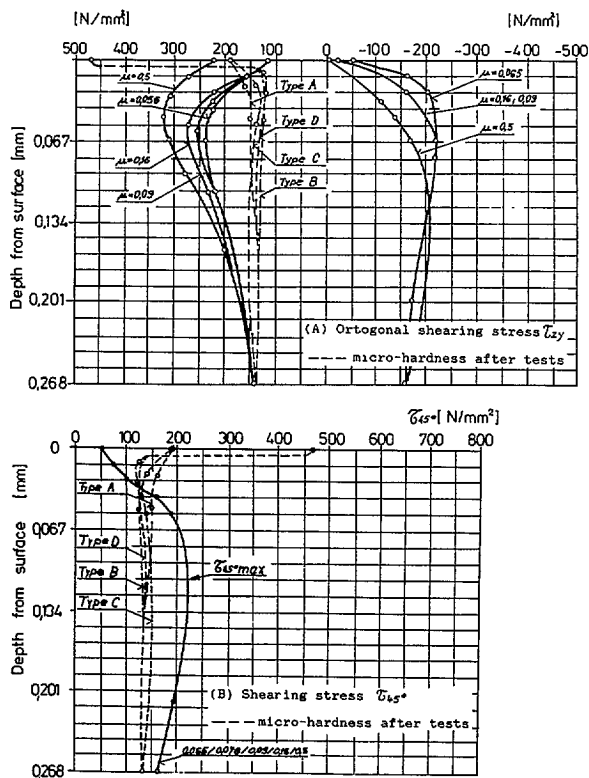


Figure 13 Distribution of reversed shearing stress and flow shearing stress on and below the surface at the incipient stage of failure

the upper roller pairs after the failure was approximately equal to the depth where the modification of the structure occurs due to the action of the orthogonal shearing stress.

6. CONCLUSIONS

The failure resistance and frictional characteristics of the roller pairs of which one was TiN coated and the other heat treated were measured using a two-roller machine. On the basis of microstructure observations of the failure measurements of hardness of this part and the calculation of the stress resulting from the combination of contact stress field and the friction force the following results were obtained

The calculated ratio of oil film thickness to combined surface roughness was from 0.095 to 0.248, indicating that the tests were run under several conditions. The coefficient of friction of the TiN coated roller pairs was higher than that of the uncoated heat treated roller pairs by about 17-28 %. The wear track in the direction of frictional force was smoother than that before the tests

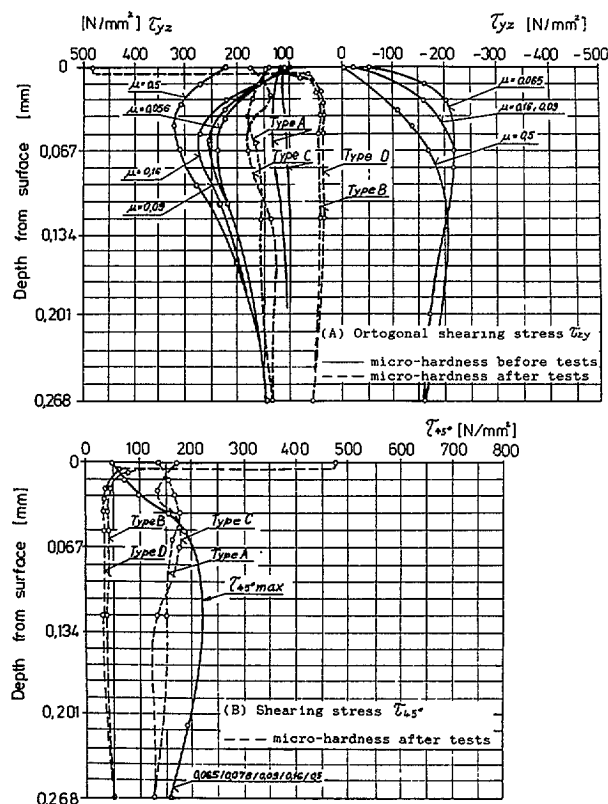


Fig 14 Distribution of reversed shearing stress, shearing stress and flow shearing stress on and below the surface at the incipient stage of failure

By testing under unlubricated conditions the lifetime of the TiN coated roller pairs was longer than that of the heat treated roller pairs by about 40 %. At the incipient stage of failure the sum of the bulk and flash temperature was higher than the A_{C_2} temperature. This confirms that an approx 1 μm thick layer of austenite was formed on roller pairs along the failed surface on the heat treated rollers.

The surface fatigue damage stage on all types of roller pairs was dependent on the value of the coefficient of friction and distribution of microhardness in the vicinity of the contact surface

The surface fatigue damage of the TiN coated roller pairs was independent of the temperature rise on the contact surface directly

The results of this investigation show that a beneficial effect of TiN coatings on the failure resistance and wear characteristic can be expected only when the base material is heat treated and the contact surface is very smooth before the coating is applied

The depth where fracture of the roller occurs due to the action of the reversed shearing and shearing stress agrees well with the calculated value

7 ACKNOWLEDGEMENTS

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