ASPERITY DEFORMATION DURING RUNNING-IN

JØRGEN JAKOBSEN AND ION M. SIVEBAEK*
Mechanical Engineering, Technical University of Denmark, 2800 Lyngby, Denmark.
Corresponding author*: ims@mek.dtu.dk

Abstract: asperities loaded in pure rolling against a hard, smooth surface will often be deformed at the first contact event and will thereby experience high normal stress, presumably of a magnitude near the Vickers hardness of the softer material. Continued running-in can be imagined to develop into lower stress levels and an increase of contact area. An asperity model simulating a running-in process of rough surfaces with lengthy protractions in the rolling direction was investigated. After a limited range of only about 10^4 contact events a state of very low deformation rate was found.

Key words: asperity, running-in, deformation, fatigue.

INTRODUCTION

Surfaces of machine elements have often protracted asperities in one direction and a small size across after the final grinding. The main direction of the protraction is in many cases equal with the rolling direction for the surfaces and represents a common type of rolling contact.

Observations of deformation behaviour of lengthy asperities subjected to rolling in the length direction are not frequently found. It was therefore considered to be of interest to follow in detail the process in the initial range of contact events until a stable condition occurs for a protracted asperity. Which pattern of deformation and stress would an asperity top follow during repeated contact events?

An asperity is exposed to high normal stress at the first contact with an opposing bearing area. The material yields. The summit ends up flat-pointed. The normal stress, p, of the contact area can be around 3 times the yield stress [1] of the material of lowest Vickers hardness at the first contact. The contact situation can therefore, to some extent, be compared with a HV-test.

As the running-in process proceeds the summit material will expectedly be further deformed plastically until the contact area can sustain the pressure. The nominal area is often and in general much greater than the effective contact area, e.g. [2, 3].

Load carrying capacity of an asperity depends on the top angle as also found with indenter tests, although trends differ in details: e.g.: [1], cone vs. plane, for work hardened copper against steel, or [4], steel cone against sapphire plane.

Nominally flat surfaces with asperities in contact have been investigated e.g. [5, 6]. A mechanism of plasticity index, [7] for spherical asperities has been discussed. A numerical value: 1, indicates a criterion of deformation mode. A simplified plasticity index $P_e = (E` \times \varepsilon_{ov})/H$ has been formulated [3]. E` is the effective modulus of elasticity, e.g. [8, 9], of the two materials of the contacting surfaces. H is hardness. The slope at the top is the magnitude ε_{ov}. Examples of typical slope values are: ground surfaces: $\cong 30^0$, honed surfaces: $\cong 4^0$, lapped surfaces: $\cong < 1^0$. For ball bearing material, [E` ≅ 228 GPa, H ≅ 8 GPa], the P_e concept indicates plastic behaviour for slopes > ≅ 3,5 %, or ≅ 2^0. The influence of very low roughness of surfaces has been discussed [10] though concerned primarily in the elastic range, and with lubricant.

Change of roughness profiles after running-in has, expectedly, shown a smooth-out effect [7] of the asperity tops but is stated to cause no significant change of topography [11]. Also: hand-polishing of a near Gaussian height distribution rough surface has demonstrated two well defined ranges with different Gaussian height distributions [5].

Rolling fatigue of non-conforming surfaces of “Maschinenelemente” has been investigated [12, 13], however, lubricated. No “Grübchen” was demonstrated for a ball bearing material. Damage could be found as very thin flaking or peeling of surface layers, appearing after 2×10^7 rolling contact events as small and limited, grey areas of the contact traces.

In this connection is should be remarked that [12, 13] gives a limiting fatigue load of around 2,6 GPa, Hertz`ian pressure, for a 651 HB (≅ 850 HV) “Kugellagerstahl”.

EXPERIMENTAL SETUP

A configuration was set up consisting of a high hardness cylinder loaded in contact with a circumferential ridge ground out of the cylindrical outside of a needle bearing ring. The axes of the ridge carrying ring and of the roller were positioned in a parallel arrangement.

The ring has an outside diameter of nominal 60^ϕ, material of HV ≅ 830 kp/mm^2, (≅ 8,15 GPa), and was solidly supported by a driven shaft. The ring with the shaft could be rotated steadily and rpm controlled. The shaft was supported with bearings, foundation, etc. The contacting, harder roller was supported and located by the outer rings of two ball bearings mounted in a dead-weight loading beam, positioned on the foundation. The roller was free-rolling, driven by the contact with the rotating ridge of the ring.

The ridge top angle was 90^0 (semi-angle 45^0), seen in a plane containing the axis of the ring. The ridge height was 1 mm.

A dead weight force adjusted to 330,36 N ~ 330 N (33,642 kp) loaded the roller against the top of the ridge-asperity. The width of the flat-pointed track of the deformed asperity top could be observed with a mounted microscope and recorded with a camera.

PROCEDURE

The hard roller was loaded against the circumferential ridge edge with named ~ 330 N and the ring was turned very slowly one turn. The width of the track of deformed material was recorded in 3 marked angular positions. This approach was repeated for each single revolution no. 2, 3, 4 and 5. The hard roller, a smooth Sapphire rod, 20^ϕ , showed slight surface damage and was replaced.

Rotation no. 6 to 10 was thereafter carried out with a new Sapphire rod, also with a diameter of 20^ϕ. The track width was recorded after the 10th rotation at the 3 marked angular positions. The new Sapphire rod showed, however, also a slight surface damage at rotation no. 10. It was therefore decided to replace the Sapphire with a smooth steel roller of a cylindrical roller bearing quality. The diameter of the roller was 16^ϕ. Hardness was above HV: 900 kp/mm^2 (> 8,84 GPa). The hard steel roller was able to sustain the remaining impressions. Recordings of the track width (w) were performed at 20, 50, 100, 200, 500, 1000, 2050, 5000 and 9500 electric motor driven rotations at the 3 marked angular positions. The experimental setup is shown in figure 1.

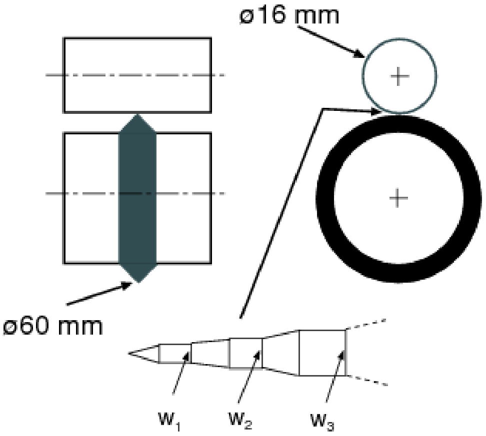

Figure 1. The experimental setup also showing the track widths w. For more details, see text.

THE MEASUREMENTS

The average width w_1 of the ridge top deformation at the 3 marked angular positions is found to be 94,3 μm, APPENDIX. The 90^0 top angle of the ridge gives a calculated plastic deformation of 47,15 μm disregarding the effect of the displaced material. The w_n values measured are presented also in the APPENDIX.

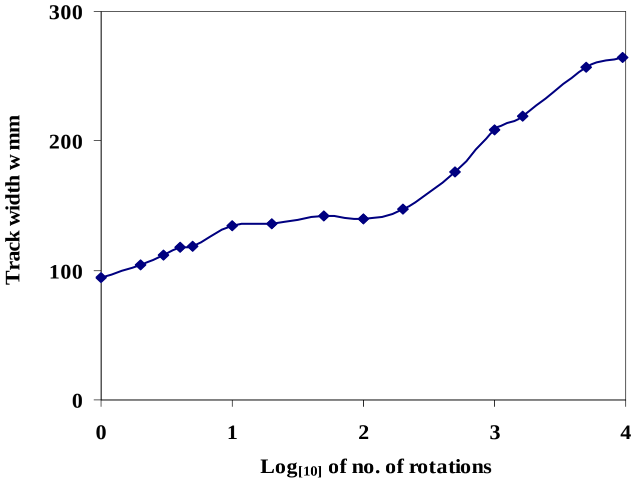

Figure 2. Ridge track width w vs. Log$_{[10]}$ of no. of rotations, w in μm.

The measured width, w, is shown in the figure 2 and in table 1. In the range 1 – 10 contact events a nearby linear increase of the width is seen as a function of the log$_{[10]}$ of the no. of rotations. The increase is from 94,3 μm to 134,2 μm, Δw = 39,9 μm or 4,43 μm per event. A modest increase is found in the range 10 – 100 contact events, from 134,2 μm to 139,7 μm. The difference is 5,5 μm or 0,061 μm per event. In the range 100 – 5000 rotations the increase is up to 257,3 μm, a Δw = of 117,6 μm or 0,024 μm per event. From 5000 to 9500 events, to 264,6 μm at 9500 events, a very low increase, 7,3 μm, is seen. This rate is as low as 0,0016 μm per event. Further change may be expected to be insignificant as a level of yield strength is reached.

Table 1. Track width w_n after n rotations of the ring – ridge.

n (-)	w (μm)	w/n (μm)
0	0	-
1	94.3	94.3
10	134.2	4.43
100	139.7	0.061
5000	257.3	0.024
9500	264.6	0.0016

A MODEL OF INTERPRETATION

An ideal elastic-plastic material behaviour is presumed.

During the no. 1 turn of the ring with the ridge a plastic deformation is anticipated.

When the roller works its way, at the no. 1 turn, flattening the ridge top, the plastic contact area can be approximated with a projected, equilateral triangle with a base line equal to the measured width w_1 of the ridge track and a triangle height h_1. The depression d_1 of the ridge top can be taken to be half of the width w_1, due to the top angle of 90^0, that is: a slope of 45^0. A simple trigonometric consideration gives $h_1 = (d_1 \times 2R_e)^{½}$, in that $d_1 << 2R_e$, where R_e is the effective radius, fx.: [8]: $1/R_e = 1/r_{roller} + 1/_{ring,\ ridge}$. The contact area

A_1 is then: $½×h_1×w_1$ or $h_1×d_1$. A_1 can also be written as: $½×w_1×(R_e×w_1)^{½}$.

The normal stress p is the ratio of the force (330,36 N ≅ 33,642 kp) over the above calculated area of contact.

The calculated, normal stress p is 8,39 GPa (854,8 kp/mm^2) after the no. 1 turn of the ring with the ridge. This is well within the size of the measured HV-value 830 kp/mm^2 of the ring-ridge material.

A greater width w_2 than the width w_1 is measured after the no. 2 turn of the ring implying a further depression d_2 of the ridge top. In a contact pressure consideration it is seen that rate of area size decreases rapidly after the no. 1 turn. The no. 1 turn creates a contact track at the top. The line contact of the roller with the track can be estimated to carry a considerable part of the force (330,36 N) after the no. 1 turn. An exact and simple approach to distinguish between plastic and elastic load distribution appears not to be practicable.

The maximum Hertz'ian pressure of the roller on the created track on the ridge top can, however, be assumed to give an order of magnitude of a lower limit of the pressure. The calculated maximum Hertz'ian pressure of the free rolling roller on the track is around 4.7 GPa. This pressure will diminish as the track width w_n increases with increasing no's of rotation.

DISCUSSION

The elastic spring back of the ridge material can be presumed to have no significant influence on the magnitude of the contact area.

A hardness test with a Vickers diamond is considered to be a one time event with a one time plastic deformation. A similar one time perception could be proposed for the circumferential impression produced during the no. 1 turn of the ridge. If, however, the Vickers diamond is applied again in the same location, that is; in the same Vickers mark then this action appears not to produce any significant further increase of the indention mark, even after several applications. There is no more significant plastic deformation. The plastically deformed material in and around the Vickers mark can carry the load, apparently in an elastic process. In contradiction to this it is found in the ridge top - roller situation that the width w_n increases with number of contact events.

A calculation of a purely elastic line contact situation after the No. 9500 rotation of the ridge yields 2,668 GPa, for a contact length: 264,6 μm, a R_e : 6,358 mm and a load: 330,36 N. A contact dimension ⊥ the width direction w_n is calculated to: 2×297,83 μm = 595,66 μm. The average pressure of the elastic model is then 2,668×(π/4) μm = 2,095 GPa.

It is plausible that the contact behaviour is primarily elastic over the main range of rotations, after about the no. 1 rotation, with only a smaller contribution of extra plastic deformation thereafter.

The increase of w_n in the range 5000 to 9500 contact events is extremely low. Significant further deformations can therefore not be expected. A fatigue limit for asperity strength of ball bearing steel can be assumed to be ascertained, around p_{max} of 2,6 – 2,7 GPa and a p_{avr} of around 2 GPA, in correspondence with earlier statements: [12, 13].

The expected, general behaviour of a loaded asperity top subjected to rolling contact can as such be described independent of model of interpretation by the measured width w_n as a function of the number of rolling contact events, figure 2.

CONCLUSIONS

A model asperity top, a circumferential ridge, top angle 90^0, of ball bearing steel, reaches in contact with a coaxially arranged, freely rolling cylinder a normal average surface pressure level of 2 GPa ($\cong$ 2,6 GPa Hertz´ian normal stress) after 9500 contact events.

The first contact gives a plastic deformation with a normal pressure equivalent to the Vickers hardness, HV, of the lower hardness material.

A magnitude level of only 10^4 contact events is sufficient to change from an assumed plastic behaviour to a nearly elastic situation where further dimensional changes expectedly will be insignificant.

Five different regimes of w_n may be identified: 1) a first plastic impression, (94,3 µm per event). 2) 9 events with still minor plastic deformations, (4,43 µm per event). 3) Then an order of magnitude 90 events gives a very low deformation rate, (0,061 µm per event). 4) Order of magnitude 4900 events give an even lower deformation rate, (0,024 µm per event). 5) In the range 5000 to 9500 events only insignificant deformations are seen; (0,0016 µm per event).

NOMENCLATURE

Sign	Unit	Designation
d_1	mm	No 1 depression d_1 the ridge top
$d_2 = ½(w_2 - w_1)$	mm	Extra depression
$d_n = ½(w_n - w_{n-1})$	mm	Extra depression
h_1	mm	Triangle height of No 1 contact area
p	kp/mm^2 or N/m^2	Normal stress
P_{max}	N/m^2	Hertz'ian pressure
w_1	mm	Width of ridge after No. 1 contact
w_n	mm	Width of ridge after No. n contact
$A_1 = ½\times w_1\times(R_e\times w_1)^{½}$	mm^2	Area of No. 1 contact
E	GPa	Modulus of elasticity
$E` = E/(1-\nu^2)$	GPa	Effective modulus of elasticity
HV	kp/mm^2	Vickers Hardness
H	N/m^2	Hardness
$P_e = (E`\times \varepsilon_{ov})/H$	-	Index of plasticity
$R_e = (1/r_{roller} + 1/ r_{ring, ridge}.)^{-1}$	mm	Effective radius
ε_{ov}	-	Slope of asperity
ν	-	Poisson`s ratio

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APPENDIX

Measured values

Rot.No	w_n µm
0	0
1	94,3
2	104,1
3	112,1
4	117,6
5	118,8
10	134,2
20	136,0
50	142,1
100	139,7
200	147,0
500	176,4
1000	208,3
2050	219,3
5000	257,3
9500	264,6