A THEORETICAL AND EX[redacted]F
CRITICAL TEMPERATURE OF BOUNDARY
LUBRICANTS AND MECHANISM OF
SCUFFING OF STEEL
SURFACES

by

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CERTIFICATE

This is to certify that the thesis entitled "A Theoretical and experimental analysis of critical temperature of boundary lubricants and mechanism of scuffing of the steel surfaces', being submitted by Mr. Jagdish Prasad Sharma to the Indian Institute of Technology, New Delhi, for the award of the Degree of Doctor of Philosophy in the Faculty of Engineering, is a record of bonafide research carried out by him. Mr. Jagdish Prasad Sharma worked under our guidance and supervision and has fulfilled the requirements for the submission of this thesis, which to our knowledge, has reached the requisite standard.

The results contained in this thesis have not been submitted in part or in full, to any other university or institute for the award of any degree or diploma.

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ABSTRACT

All moving machine elements need to be protected against failure under lubrication. In gear and bearing materials the common type of failures encountered are - fatigue, galling, scoring, scuffing, wear etc. Scuffing is a phenomena that mostly occurs in the face of the gear tooth and the contacting zone where sliding is prominent. This results in wear and tear of the surface due to failure of the boundary lubricants. This is accompanied with a sudden increase in the friction value at a temperature known as critical temperature. The critical temperature is greatly affected by the surface properties of the material and its structure, the hardness, the surface finish, the slide/roll speed, the surface temperature, the additives and its interaction with the surface as lubricant. All these factors make the study of the phenomenon of scuffing and critical temperature complicated.

In the present study, an attempt has been made to explain the mechanism of scuffing both experimentally and theoretically. Different steel surfaces like EN 58J (austenitic), austenatic S/S -18/8, EN 39B (case hardened)and Am 440C (martensitic, supplied by NASA with different hardness values have been experimented upon. The deformation of these soft to hard steel steel affects the critical temperature of the lubricants and their interaction with the surfaces. For carrying out this investigation, a modified Bowden-Laban machine and a ball and peg apparatus were used. The various ranges of parameters

over which experiments were carried out were as follows:

a) Surface roughness: The surface roughness was varied from 3 uin to 42.5 uin average CLA value for different steel flats.

b) Normal Load: The normal load on a half inch stainless steel ball sliding on the flat steel surfaces, using the Bowden-Leben machine, were in the range of 1 to 14 lbs. Using the ball and peg apparatus, the range of normal load was from 1 to 30 lbs.

c) Sliding speed: The sliding speed was kept constant at 0.02 cm/sec. However, to examine its effect on the critical temperature the sliding speed was varied in the range of 0.02 cm per sec. to 0.05 cm. per sec. for one set of experiments with a constant normal load on the steel ball.

d) Lubricants: The lubricants used were:

i) Esso OEP-90, REF. AOL/3070/66;

ii) Monsonto-73853-Tetravolerate penta ethythonol (supplied by NASA, USA);

iii) TH-12884 (Mineral oil), TH-9711 (High reference mineral oil), and TH 9483 (low reference mineral oil). All supplied by Sunbury on Thames, U.K.;

iv) Stearic acid as additive in squalane (medicated white oil). The concentration of additive varied between 0.02% to 0.6% by weight;

v) Amines as additives in cetane. The concentration values varied between 0.02% to 0.06% by weight.

Experimentally it is found that the critical temperature of the boundary lubricant on steel surfaces appeared as a sharp rise in the friction value which is clearly seen in the friction temperature traces. With Monsonto - 73853 oil, a sudden increase in the friction value is seen at three points giving three values for the critical temperature. This is due to the release of the free acid content at these stages. In all these cases the friction co-efficient remained constant inspite of the increase in the temperature till the critical point was reached.

The worn track width which practically remains constant with an increase in temperature also jumps up suddenly to a higher value at the critical temperature. This suggests that boundary lubrication becomes ineffective at this temperature. On the other hand, the track surface finish value remains constant even beyond the critical temperature of the lubricant. It then suddenly shoots up at a particular temperature irrespective of the normal load applied on the ball and the initial value of the surface finish of the test specimen. The value of this particular temperature is obtained by extrapolating to zero load either the friction temperature trace or the track width-temperature diagram. Both curves give the same value of the critical temperature. This extrapolated zero load temperature corresponds to the temperature at which serious surface damage occurs. This suggests that a thermodynamic study of the metal - lubricant combination may lead to an insight of the mechanism of scuffing. An explanation to this has been given in terms of the desorption work term. In all these cases it is assumed that the critical temperature in fact refers to reversible adsorption and desorption, with $\theta = \frac{1}{2}$.

If the temperature of the boundary lubricant is further increased beyond this zero-load critical temperature, the adsorption and desorption phenomena may become irreversible and the coverage value for   may go below half causing serious damage to the surface.

The interfacial surface entropy varies linearly with the applied normal load for a particular surface roughness value. Also the critical temperatures associated with the sharp rises in the friction and the track width decreased linearly with increasing load. This suggests that the surface deformation due to specific pressure has a definite role in the determination of the critical temperature of the lubricants. The amount of deformation of the surface having different surface roughness significantly alters the critical temperature values as can be clearly seen from the experimental results.

The effect of the chain length of various amines in a cetane carrier indicates a maxima for the critical temperature. The maximum resistance to temperature occurs when the number of carbon atoms of the amines matches that of the carriers.

A theoretical study has also been carried out using Gibb's free energy concept to identify the critical temperature of the lubricants. The values of heat of adsorption 'ΔH', given by the equation for the thermodynamic activity, is:

$$- \frac{\Delta H^\circ}{T_a} + \Delta S^\circ = R \left\{ \log_e \frac{\theta}{1-\theta} - \log_e C \right\},$$ where T_a is the absolute critical temperature, S° is the standard entropy change, θ is the percentage coverage of the polar molecules on the surface site due to adsorption and C is the percentage con-

- centration by weight of the polar molecule additives in the base oil. Experimental results plotted between $Log_e C$ and $(T)^{-1}$ gives a straight line and satisfies the equation quite well. The slope of this line gives the value for H for the condition $\theta = 0.5$. This concludes that the critical temperature at the onset of scuffing is a thermodynamic process in which the polar molecules of the lubricants adsorb and desorb from the surface site.

It was also observed during the course of this investigation that the energy for desorption on the steel surfaces during the sliding process is composed of the enthalpy of the polar molecules of the additives and, the activation energy due to the dislocation movement. These two energies have been identified and it has been shown that the heat of desorption is affected considerably by the surface conditions. Consequently the critical temperature changed. The values for the heat of desorption gave an optimum surface roughness value for each of the steel specimens.

An attempt has been made to evaluate theoretically, the value of the friction coefficient for the lubricated steel surfaces at the onset of scuffing. Its value normally varies between 0.3 to 0.4 and depends upon the particular surface condition of the steel specimens.

It is also seen that for a particular temperature there is a minimum limit for the percentage concentration of fatty acids that can be used in order that it becomes effective as a boundary lubricant.

An attempt has also been made to check the residence time for the adsorbed polar molecules on sites of steel surfaces at a particular temperature. This has been correlated with the time required to cross the Hertzian width in the case of the ball sliding on the plate to predict the necessary conditions for scuffing.

All these contributions help in understanding the action of additives and the mechanism of scuffing both quantitatively and qualitatively. The aim of this investigation is to give originality to arm and equip the designers in preventing failure rate of their best design.

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