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THE USE OF A LABORATORY WEAR SIMULATION TECHNIQUE FOR THE DEVELOPMENT OF MARINE CYLINDER LUBRICANTS

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Low speed, super-long-stroke (SLS) marine diesel engines present an arduous working environment for marine cylinder oils and are expected to become even more severe in the future. Evaluation of lubricant wear performance in such engines relies primarily on ship trials, making the rate at which formulation development can proceed relatively slow.

Against this background, the need for a deeper understanding of lubricant anti-wear action continues to increase and, with it, the need for more informative laboratory wear test procedures. An essential starting point in the development of the latter is a clear understanding of the principal wear mechanisms involved and of the way they relate to engine operating conditions. This paper describes an approach to wear testing which successfully simulates the corrosive environment of the SLS engine and reproduces the corrosive and scuffing wear processes that the lubricant is principally required to control. Results point to the properties of the lubricant which most strongly influence anti-wear performance.

Les conditions auxquelles sont soumises les huiles cylindres marines utilisées dans les moteurs diesel marins lents et à grande amplitude sont particulierement dures et le seront encore plus dans le futur. L'évaluation de leur résistance à l'usure repose essentiellement sur des essais à bord des bateaux, ce qui ralentit la durée d'étude et de mise au point d'une formulation.

Pour remédier à cet état de fait, il est nécessaire d'avoir une meilleure compréhension de l'action anti-usure des lubrifiants, et ce sont les informations retirées des procédures d'analyse de l'usure en Laboratoire qui approfondiront nos connaissances. Pour mettre au point de telles procédures, il est essentiel de comprendre clairement les principaux mécanismes d'usure qui sont en jeu, et leur relation avec les conditions de marche des moteurs. Ce rapport décrit une méthode d'analyse de l'usure qui simule de façon satisfaisante l'environnemont corrosif des moteurs à grande amplitude et qui reproduit les étapes d'usure corrosive et par frottement que doit controler en priorité le lubrifiante. Les résultats montrent les propiétés qui influencent le plus fortement la performance anti-usures des lubrifiants.

INTRODUCTION

The relatively high levels of piston ring wear in certain SLS marine diesel engines are caused by the corrosive environment created in the upper cylinder area by the combustion of high sulphur fuels. Since this environment affects the performance of cylinder oils in both absolute and relative terms, wear screening tests which fail to take account of it are of very little value. This poses an industry-wide problem for marine lubricant suppliers who must rely heavily on ship trials for the assessment of new formulations. Users of SIPWA ship-board wear monitoring technology are better placed as this system can provide useful information in months rather than years. These time scales are still long for research and development purposes, however, and trials can always be prejudiced by unforeseen and unavoidable practical difficulties. The attraction of an informative laboratory test thus remains very strong.

In common with other companies [1], BP has attempted to simulate the corrosive operating environment in marine engines by supplying dilute sulphuric acid to lubricated contacts in laboratory wear tests. The approach has been successful to the extent that (a) wear is induced under conditions where none occurs in the absence of acid, (b) the wear mechanism is of a corrosive nature and (c) oils previously evaluated in SIPWA trials are correctly differentiated. A problem which has been encountered with this procedure, however, is that dilute acid induces hydrolysis of a certain type of anti-wear additive which then becomes highly corrosive; distilled water has virtually the same effect. As the additive in question functions quite successfully in service, the dilute acid technique has ultimately been discarded as unsatisfactory.

Attempts to overcome the hydrolysis problem by supplying sulphuric acid in concentrated form have also proved unsuccessful. Since the total quantity of acid needed in such experiments is small, the minute feed-rate involved proves far too difficult to control.

In an attempt to resolve these experimental difficulties, lubricant has also been mixed with concentrated sulphuric acid before wear testing begins. This was not, originally, a favoured approach since pre-neutralisation of the agent intended to simulate the corrosive environment appeared to defeat the object of the exercise. In practice, such concerns have proved unfounded. Early measurements, reproduced in Table 1, showed good directional consistency with SIPWA wear measurements, carried out by the BP method [2]. The latter defines wear performance of candidate oils in terms of the percentage change in wear rate seen from that of a reference oil.

Table 1. COMPARISON BETWEEN RIG AND ENGINE WEAR MEASUREMENTS.

	Rig wear rate (µm/h)	SIPWA wear difference (%)
Oil A	0	-29
Oil B	0	-21
Oil C	0.5	-6
Reference	6.3	0
Oil E	11.1	+61

Whilst these results provided encouragement for the new technique, they also suggested that data obtained at just one screening test condition could not fully account for the range of behaviours seen in service. Oils which yield no wear in the rig test, for example, can obviously not be differentiated. To provide a deeper understanding of the way in which lubricants contribute to wear control, a more wide-ranging wear study has been undertaken and is described here.

EXPERIMENTAL

Apparatus

The test system is based on the Cameron-Plint TE-77 high frequency friction machine. This apparatus provides a reciprocating motion between a moving pin specimen and a stationary plate, the latter being attached to a small sump which also acts as the source of heat (see Figure 1). Plate temperatures of up to 600°C may be attained with this equipment, temperature control being provided by a four term, ramp and dwell temperature programmer. In a small but important modification to the design of the equipment, temperatures are always measured at the upper surface of the plate specimen and not at a side-face.

On-line measurements made in the course of each test include surface temperature, instantaneous friction force and the instantaneous electrical contact resistance between the sliding pair. Contact resistance is measured in terms of the potential difference (PD) between the test specimens, an open-circuit value of 50 mV representing a highly resistive and well-protected contact and a zero value reflecting high levels of potentially damaging metallic contact. Temperature and time-averaged values of friction and PD are logged by a microcomputer. A further addition to the apparatus is an on-line wear detection system based on a displacement transducer. Although out-of-plane movements of the reciprocating pin specimen are large in relation to those due to wear, the unwanted cyclic component is easily removed by digital filtering.

To obtain the required range of contact stress, a cylindrical pin specimen was used to obtain a nominally flat-on-flat contact geometry. The design of the pins means that some running-in is generally required before full conformity is achieved. With a pin of 2 mm diameter, loads in the range 80N to 250N yield nominal contact pressures of 25 to 80 MPa (250 to 800 bar).

Pin and plate specimens were manufactured from cast iron marine piston rings and cylinder liners, respectively. Hardnesses lay in the range 215 - 225 Hv20. Pin specimens were lapped to a finish of 0.05 µm R_a while plate specimens were ground at 45° to the sliding direction to a finish of 0.50 - 0.70 µm R_a.

Test method

Tests were initiated with a 20 minute, lightly loaded running-in period over which the plate was raised to 50°C. At the end of this period the full load was applied and datalogging started. A second, 30 minute temperature ramp raised the plate temperature to 250°C, a condition maintained for the remaining six hours of the test. On completion of each test, pin and plate specimens were cleaned with petroleum ether and stored in a dessicator for later metallographic examination.

Lubricants

Studies of wear mechanisms centred mainly on three cylinder oil formulations of 50, 70 and 100 Base Number (BN). Experiments addressing the influence of lubricant basicity on wear involved two additional grades of 10 BN and 20 BN. The same additive chemistry was used in all five formulations.

As mentioned earlier, lubricants were pre-mixed with concentrated sulphuric acid to simulate the corrosive environment within the combustion chamber. Mixing of oil and acid was effected using a stirrer fitted with a dissipator head over a period of about five minutes. The resulting emulsion was drawn into a plastic syringe, care being taken to exclude any foam produced by the acid-base reaction. Table 2 illustrates the effect of typical acid treatments for the three oils of central interest.

The addition of sulphuric acid to the lubricant obviously reduces Base Number to a lower "residual" level, the value of which can be calculated if all of the acid is assumed to have been neutralised. Although the validity of this assumption needs to be questioned, it provides a useful initial framework around which interpretation of experiment can be built up.

Table 2. EXAMPLES OF THE EFFECT OF SULPHURIC ACID ON CALCULATED RESIDUAL BASE NUMBER.

% wt acid	100 BN	70 BN	50 BN
0	100.0	70.0	50.0
1.5	83.0	53.4	32.9
2.5	71.6	42.2	21.6
3.5	60.2	31.1	10.3
4.5	48.9	20.0	-1.3
5.5	37.5	8.9	-12.5
6.5	26.1	-2.2	-23.9
7.5	14.8	-13.0	-
8.5	3.4	-24.4	-46.2
9.5	-8.0	-	-

(N.B. - negative values indicate that the oil is acidic)

RESULTS

Typical results for a fresh (i.e. non-acidified) cylinder oil are shown in Figure 2. The uppermost of the three traces illustrates the variation in friction with time, the middle trace the variation in PD and the bottom trace wear of the pin (plate wear is always small in comparison). Negative wear indications at the start of the experiment reflect thermal expansion of the apparatus during the temperature ramp. Clearly, wear can only be determined under conditions of constant temperature. Over the constant temperature phase of the experiment, active film formation is indicated by the PD trace, the boundary film becoming increasingly well-established as the test proceeds. Wear is negligible.

Addition of acid to the lubricant inhibits boundary film formation, eventually to the point where evidence of film formation can no longer be detected. 3.5% wt. acid added to the 50 BN cylinder oil produces such a condition in Figure 3. A steady-state wear regime is also evident.

Specific wear rates

A succinct view of the influence of load is obtained when wear is first expressed in terms of specific wear rates. The specific wear rate, k, derives from the laws of dry (i.e. unlubricated) wear and defines the volume of material worn away per unit sliding distance per unit load [3]. Thus:-

$$k = V/(W.s)$$

where V is the wear volume, W the load and s the sliding distance. Dry wear theory is readily extended, conceptually, to include the influence of boundary films [4]. In either case, k is expected to be independent of operating conditions such as load and speed and responsive only to changes in surface condition. This might be the state of oxidation of the surface in the dry case or the rate of acid attack in the boundary case of interest here. Temperature can change the state of the surface in either case.

Expressed as specific wear rates, data obtained for 50, 70 and 100 BN lubricants at three loads take the form shown in Figure 4. Specific wear rates are essentially independent of load in the corrosive wear regime, indicating that the magnitude of the contact stress does not influence the nature of the wear phenomenon.

At high load and low acid levels, scuffing occurs. Scuffing behaviour varies with the initial Base Number of the cylinder oil. Although higher peak wear rates are observed at high BN, the scuffing problem is brought more quickly under control as acidity rises. As BN decreases, in Figure 4, greater overlap is seen between scuffing and corrosive wear regimes. In any particular experiment, either or both types of behaviour may be observed in the overlap region, probably being influenced by the degree of running-in achieved during the conditioning phase of the test.

Metallographic examination

Identification of "white-layer" transformation structures in experiments where severe wear occurred confirmed the incidence of scuffing. Under corrosive wear conditions, the microstructure of the flake graphitic cast iron material appeared etched, areas of phosphide eutectic being clearly evident within a pearlitic matrix. This is diagnostic of a corrosive wear regime [5].

DISCUSSION

Scuffing

The observation that scuffing occurs under highly stressed, low acid conditions is consistent with operating experience. Scuffing tends to be a particular hazard during running-in, where stress concentrations are induced by new rings in much the same way as by edge-loaded pin specimens in the laboratory test. The low sulphur fuels used during running-in lead to relatively low levels of acid gas formation within the engine and, this too, increases the danger of scuffing.

The corrosive wear threshold

Used oil analyses in ship trials indicate that, in its single pass through the cylinder bore, a 70 BN lubricant may experience a reduction in base number to 30 or even 20 BN, depending on the sulphur content of the fuel. This corresponds to acid levels in the range 3.5% - 4.5% wt. in the wear simulation test, the range over which corrosive wear is first detected in Figure 4. As might be expected, traditional 70 BN lubricants offer sufficient basicity to prevent the onset of severe corrosive wear.

Figure 4 shows that, at the load levels representative of non-scuffing running conditions, wear can not be detected until the acid concentration exceeds a critical level (i.e. until the residual BN of the lubricant has been sufficiently reduced). Attempting to induce measurable corrosive wear in the low acid region through an increase in load does not succeed; a catastrophic transition to scuffing occurs instead. The absence of wear at low acid/high BN conditions can be explained if the base content of the lubricant is assumed to consist of active and relatively inactive fractions. Addition of acid to the lubricant is then likely to consume the active portion first and reduce BN to the calculated residual level. At the wear threshold, active base will have been fully neutralised. Beyond that point, acid and base may either co-exist within the lubricant or react at a rate which is too slow to prevent acid attack on the surfaces. Corrosive wear is obviously to be expected under such circumstances, the rate of wear increasing roughly in proportion to the concentration of free acid. For a given lubricant chemistry, the rate of increase might also be expected to be independent of the initial Base Number. This view of the acid-base interaction is consistent with the behaviour seen in Figure 4.

Wear maps

The threshold acidity level at which corrosive wear starts provides the basis for a new measure of product quality. Figure 5 illustrates how it has been used to inter-relate the wear protection characteristics of a range of products based on similar lubricant chemistry. From the residual BN at the wear threshold, an "Active BN" content has been defined for each oil as:-

Active BN = Initial BN - Residual BN at the wear threshold

An approximately linear relationship between Active BN and Initial BN obtains up to an Initial BN of about 70, with a slope of about 0.56. Just over half the base thus appears to be active in this type of product. Above 70 BN, the rate of increase in Active BN decreases noticeably. Increasing Initial BN from 70 to 85, for example, increases the Active BN content only by about 6.

Experiments with different lubricant chemistries have shown that the active fraction of the base can vary widely and is influenced by both the additive system and the base oil. Figure 6 illustrates the range of variation observed in tests with experimental formulations. It will be noted that the potential benefit to be gained from a careful optimisation of a 70 BN lubricant is significantly greater than may be achieved by increasing the Base Number of a less effective formulation to, say, 80 or 85.

It is, of course, to be expected that, in an operating engine, the potential benefits of cylinder lubricants may not always be fully realised. Although the lubrication regime in the laboratory test is boundary, for example, a copious supply of lubricant is always available to replenish protective boundary films. Under the more sparingly lubricated conditions in an engine, boundary film formation may be less robust even in the "safe" region above the Base Number threshold.

CONCLUSIONS

A new experimental approach has been developed to model the simulation of piston ring wear in super-long-stroke marine diesel engines. Using concentrated rather than dilute sulphuric acid to simulate the corrosive operating environment eliminates undesirable side-effects caused by hydrolysis.

Scuffing occurs in wear tests when the contact stress is high and acidity low. This is consistent with field experience where scuffing tends to be most problematical during running-in.

At less severe contact stresses, a sharp transition from wear-free conditions to steady-state, corrosive wear occurs at a critical acid concentration. The hypothesis that this represents the point at which the most active portion of the detergent system has been fully neutralised provides a satisfying explanation of the experimental observations. It also provides a means by which different lubricant chemistries can be differentiated in terms of their active base fractions.

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REFERENCES

1. G. Lane, P.G. Casale & R.E. Chadwick, DEVELOPMENT OF MARINE LUBRICANTS FOR THE FUTURE LOW- AND MEDIUM-SPEED ENGINES, *Ind. Lubr. & Trib.*, February 1988, 4-13.

2. A J Langer & J R Hull, THE CONTINUOUS MONITORING OF WEAR IN LOW SPEED MARINE DIESEL ENGINES AND TECHNIQUES FOR ASSESSING LUBRICANT PERFORMANCE, A Seminar on Experimental Methods in Engine R&D, I. Mech. E., London, March 1988.

3. J. F. Archard, CONTACT AND RUBBING OF FLAT SURFACES, *J. Appl. Phys.*, **24**, 1953, 981-988.

4. C. N. Rowe, SOME ASPECTS OF THE HEAT OF ABSORPTION IN THE FUNCTION OF A BOUNDARY LUBRICANT, *Trans ASLE*, 9, 1966, 100-111.

5. T.S. Eyre, K.K. Dutta & F.A. Davis, CHARACTERISATION AND SIMULATION OF WEAR OCCURRING IN THE CYLINDER BORE OF THE INTERNAL COMBUSTION ENGINE, Paper C375/029, Combustion Engines - Reduction of Friction & Wear, I. Mech. E., 1989, 125-129.

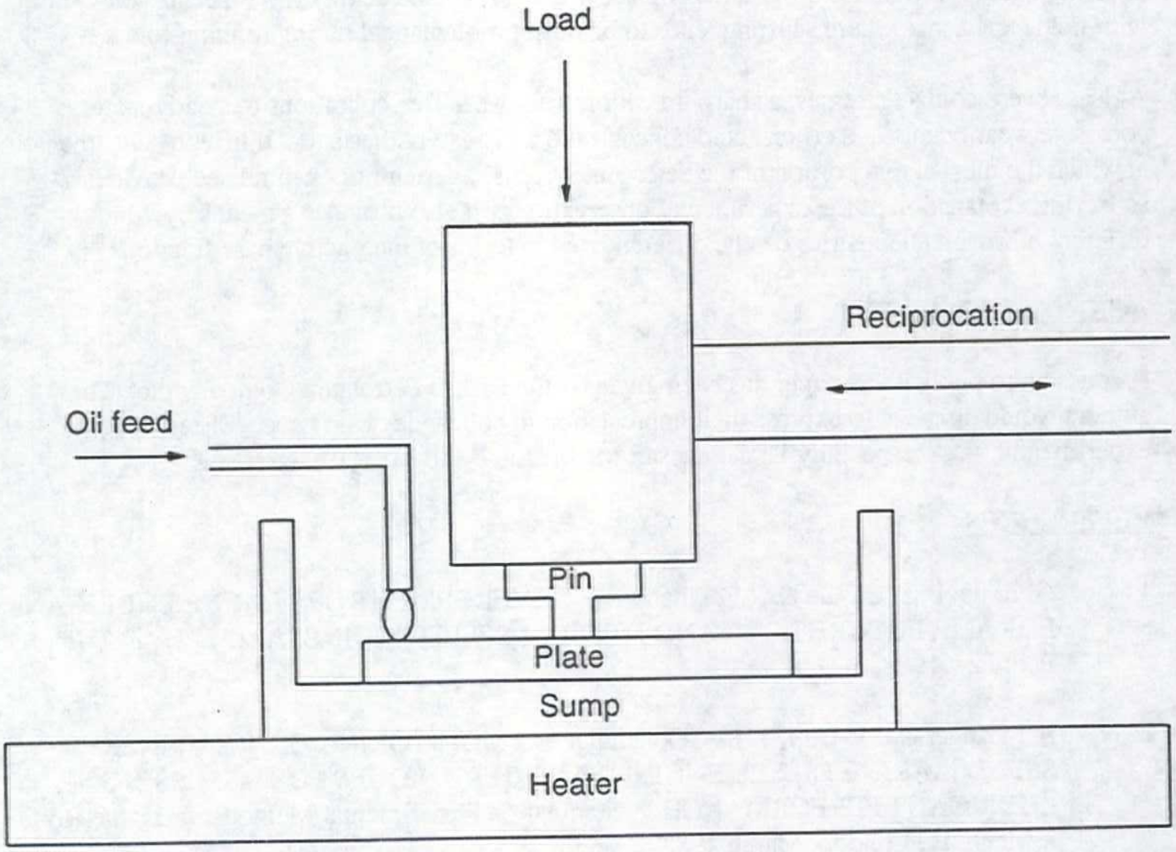

Figure 1. Specimen arrangement in the Cameron-Plint machine.

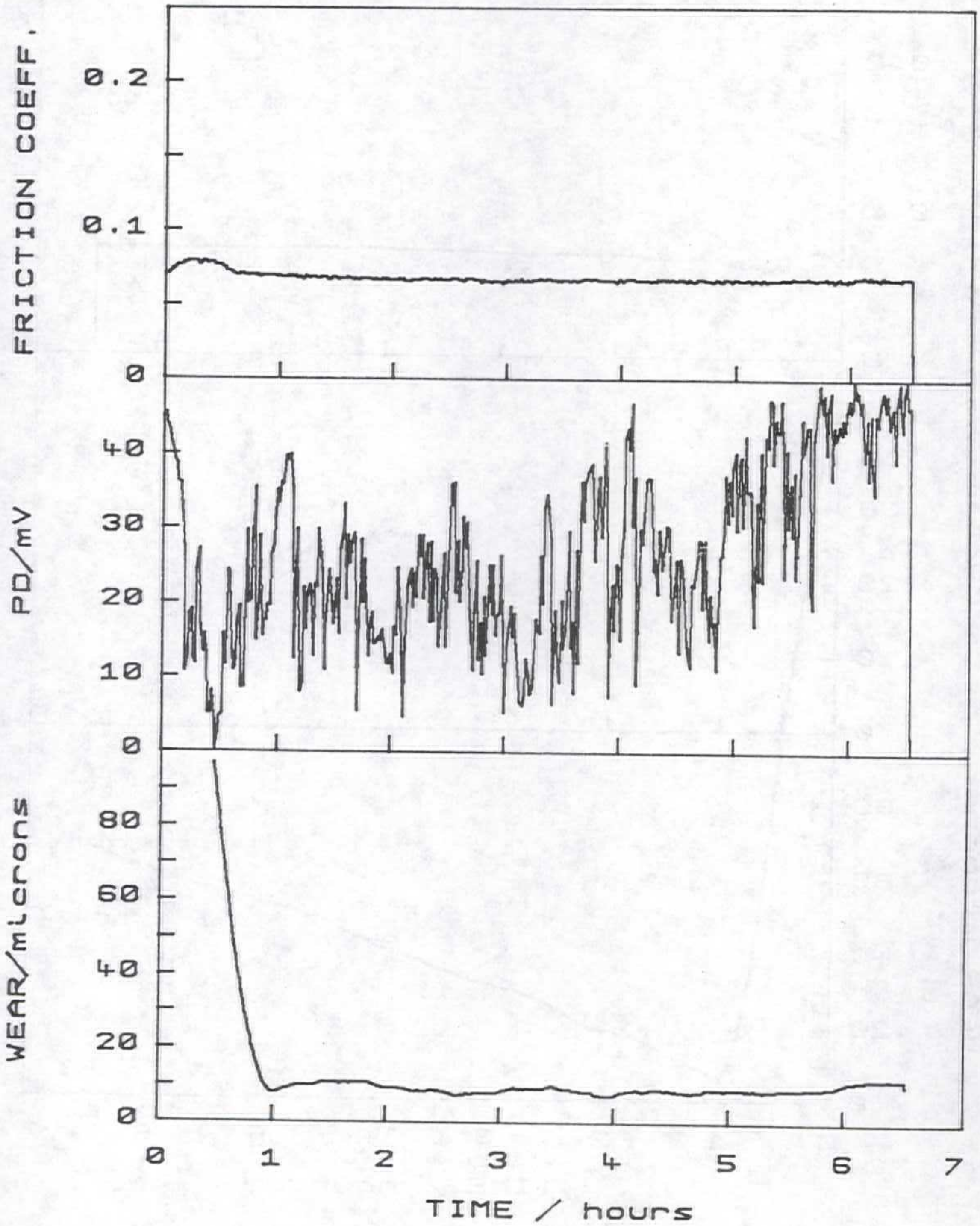

Figure 2. Behaviour of 50 BN cylinder oil at 80N load.

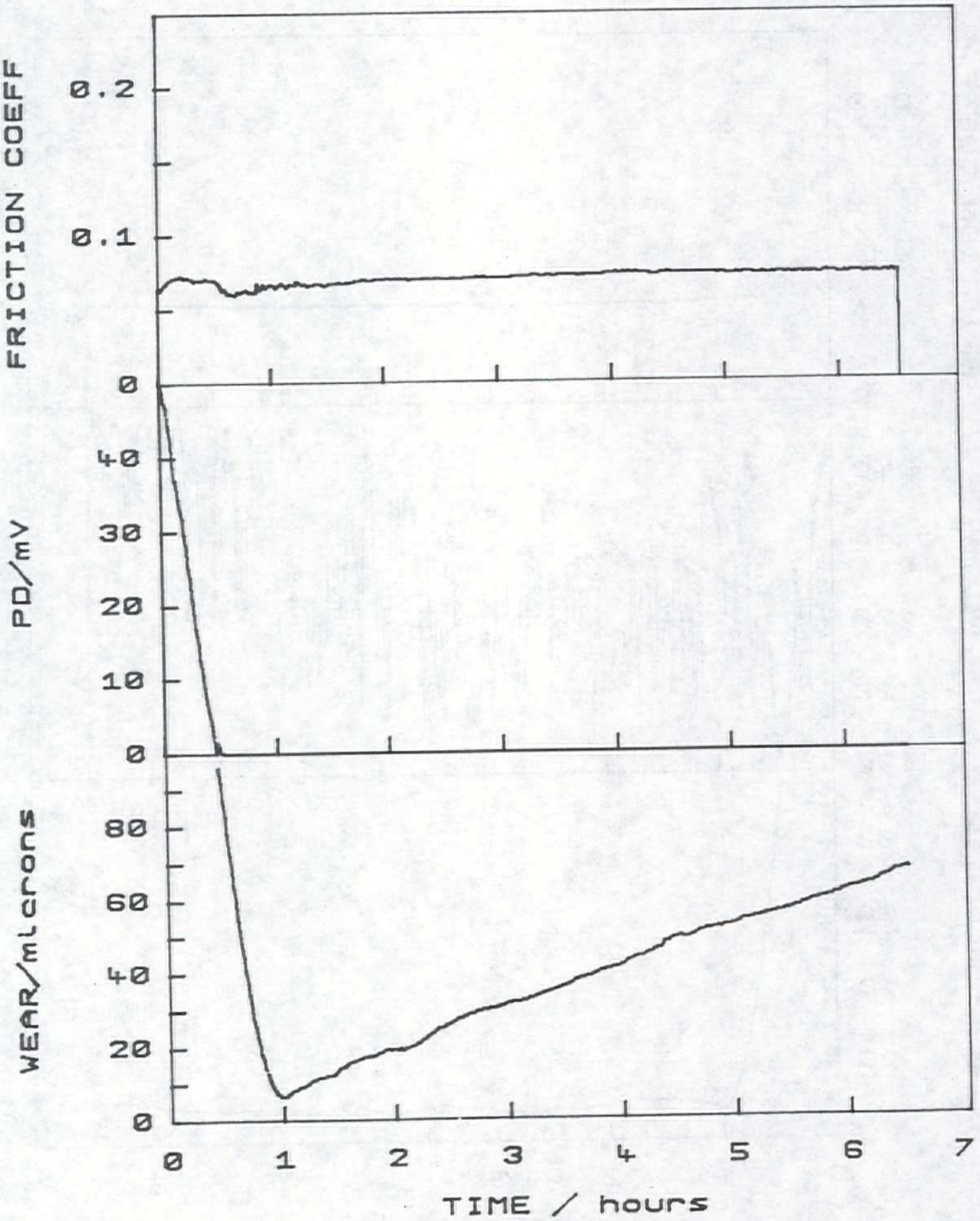

Figure 3. Behaviour of 50 BN cylinder oil at 80N load after treatment with 3.5% wt. sulphuric acid.

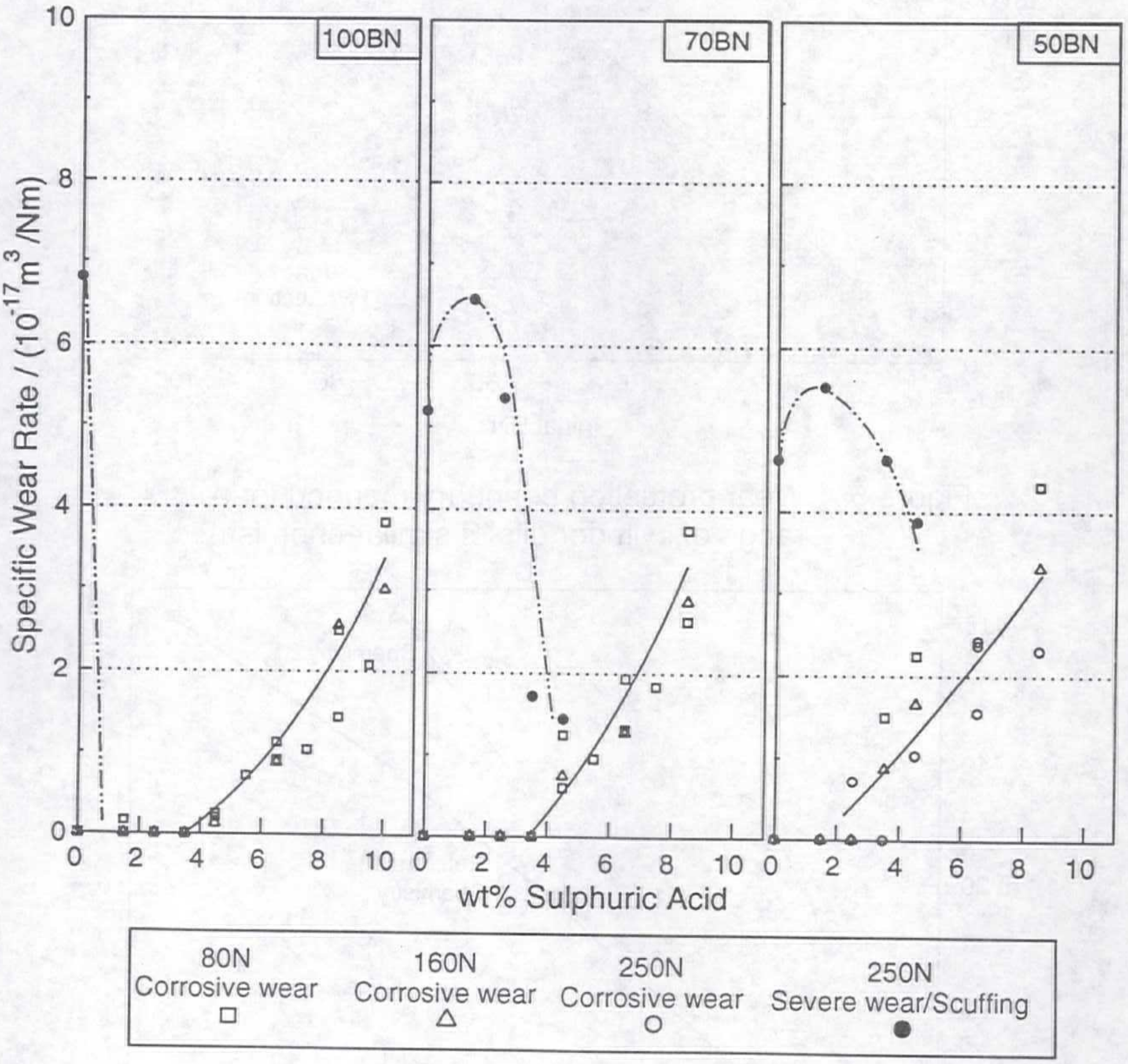

Figure 4. Specific wear rates for 50, 70 and 100 BN cylinder oils.

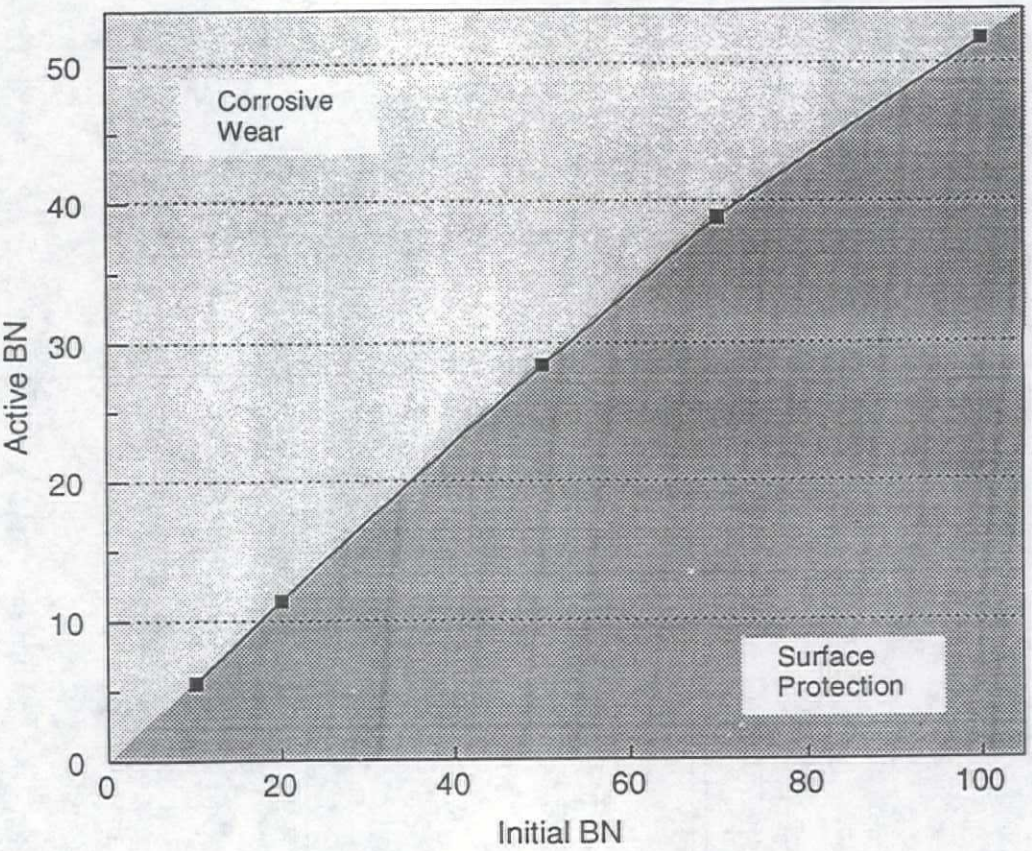

Figure 5. Wear protection boundary mapped for a range of cylinder oils of similar chemistry.

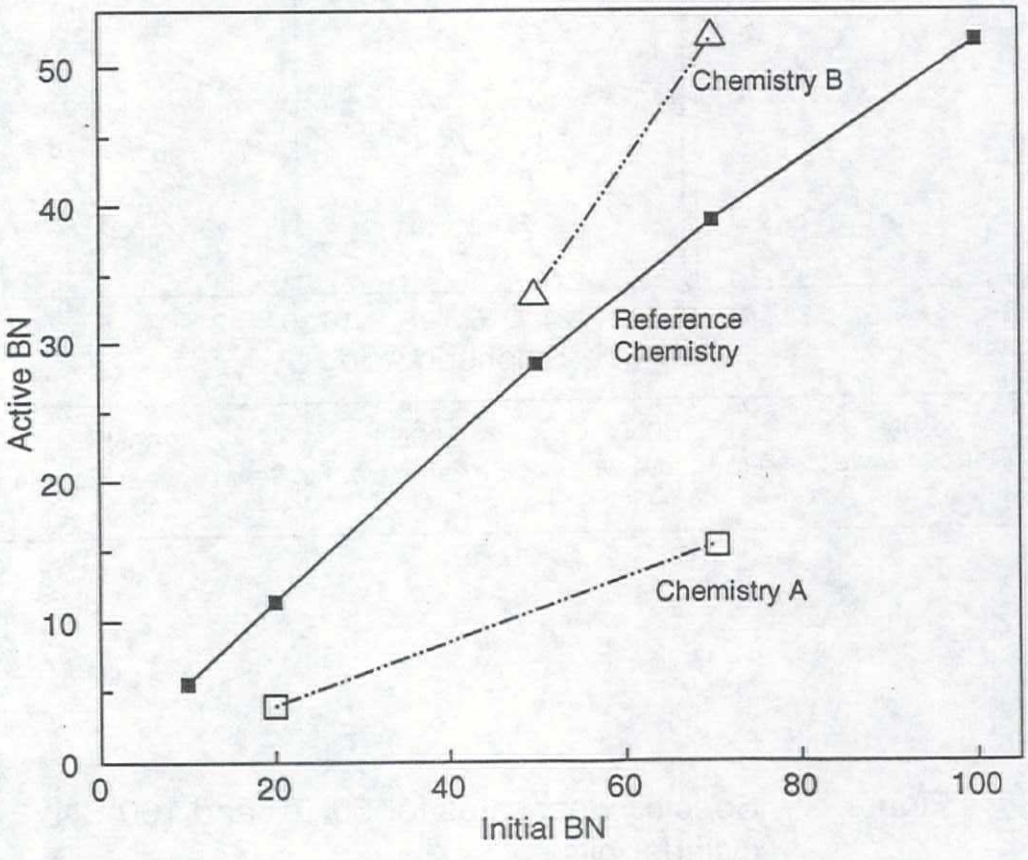

Figure 6. Wear protection boundaries for different cylinder oil chemistries.