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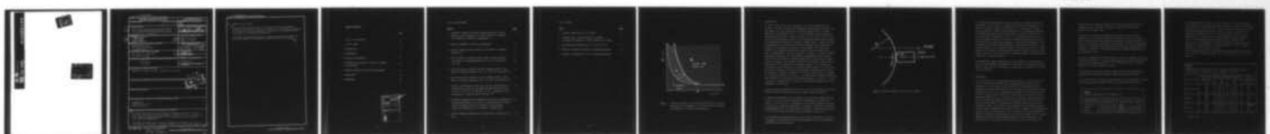

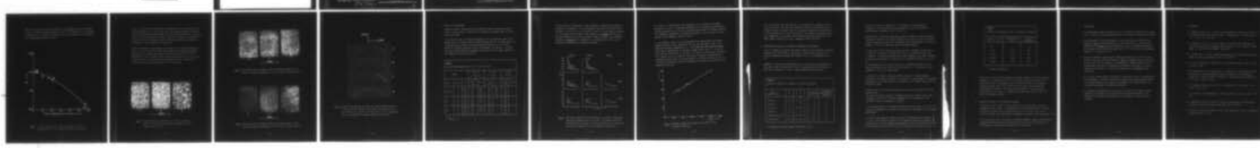

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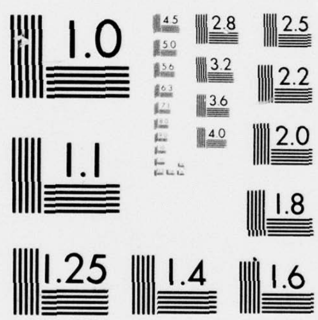

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The lubrication condition of sliding concentrated steel contacts can be described in terms of transition diagrams, relating the mode of lubrication (i.e. (partial) elastohydrodynamic (EHD), boundary and unlubricated) to load, speed and temperature.

Increasing the percentage of alloying elements of the steel (i.e. from 1.5% Cr to 5.2% Cr, 1% Mo, 0.2% V) seriously impairs the load carrying capacity → over

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20. Abstract (continuation)

of the boundary lubricant film, while that of the EHD film remains unaffected. Formation of retained austenite (with corresponding coarsening of the structure and some decrease in hardness) mildly impairs boundary lubrication but enhances EHD lubrication.

The results are compared to those of other authors and conclusions are drawn with respect to correlations between the test methods used.

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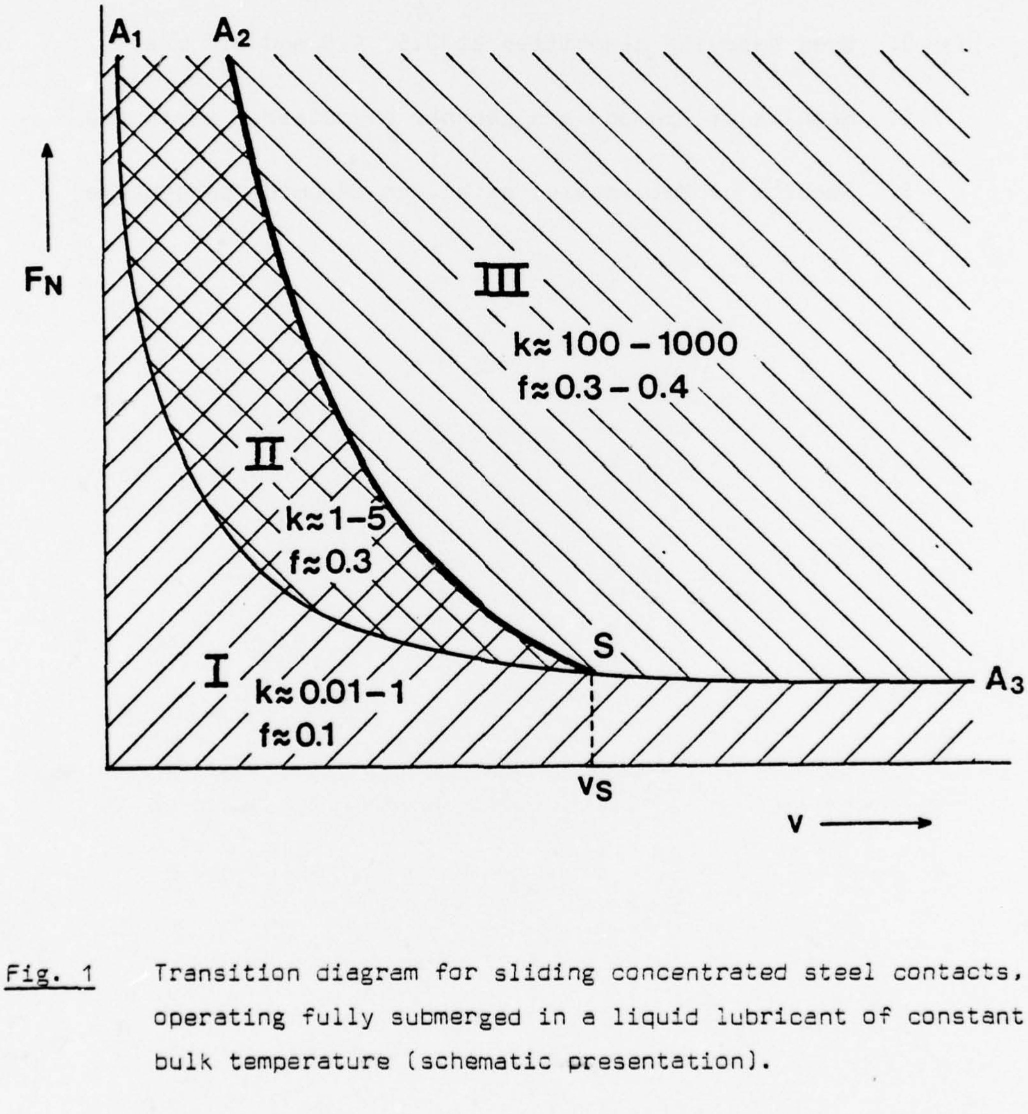


Fig. 1 Transition diagram for sliding concentrated steel contacts, operating fully submerged in a liquid lubricant of constant bulk temperature (schematic presentation).

1. INTRODUCTION

In 1975 a study of thin film lubrication of sliding concentrated steel contacts, the results of which are supposed to be applicable to gears, cams and tappets, etc. was supported by Army Grant DAERO-75-G-050. The work resulted in a contribution (ref. 1) to the 1976 ASME Lubrication Division Spring Conference, held in Atlanta, Georgia, May 24 - May 26, 1976. It was found that the lubrication condition of sliding concentrated steel contacts can be described in terms of a transition diagram (Fig. 1), giving the mode of lubrication of the system as a function of normal load F_N and speed of sliding v. This diagram is believed to be descriptive for lubrication, lubricant film failure and scuffing in gears. Strong indications are found that, at combinations of F_N and v which fall in region I, a partial elasto-hydrodynamic lubricant film (incompletely) separates the steel surfaces. This film survives asperity contacts because newly formed contacts oxidize rapidly. Collapse of the lubricant film occurs if oxidation cannot longer keep ahead of the formation of new asperity contacts. As a consequence, increasing surface roughness and decreasing oxygen content of the lubricant both cause a reduction in load carrying capacity. Depending upon the value of the speed of sliding, collapse of the EHD film either leads to a regime of "incipient scuffing" (II in Fig. 1), in which boundary lubrication effects still persist or to severe wear and scuffing (region III of Fig. 1) in which the system is supposed to run virtually unlubricated (although still fully submerged in the oil bath).

The above results explained many if not all of the controverses that existed between different theories on scuffing in gears, cams and tappets.

An important consequence of the existance of a transition diagram as shown in Fig. 1, is that it can be applied in characterizing lubricants with respect to their reaction to overloading. For different additives this was illustrated by performing experiments in lubricants, containing zincdialkyl-dithiophosphate (ZDP) and dibenzyldisulfide (DBDS), respectively (see Figs. 11 to 15 of the annual technical report of DAERO-75-G-050; ref. 2).

In the present program the objective was to define more clearly the role of the <u>steel</u> in the lubrication and scuffing phenomena that are encountered in concentrated contact situations.

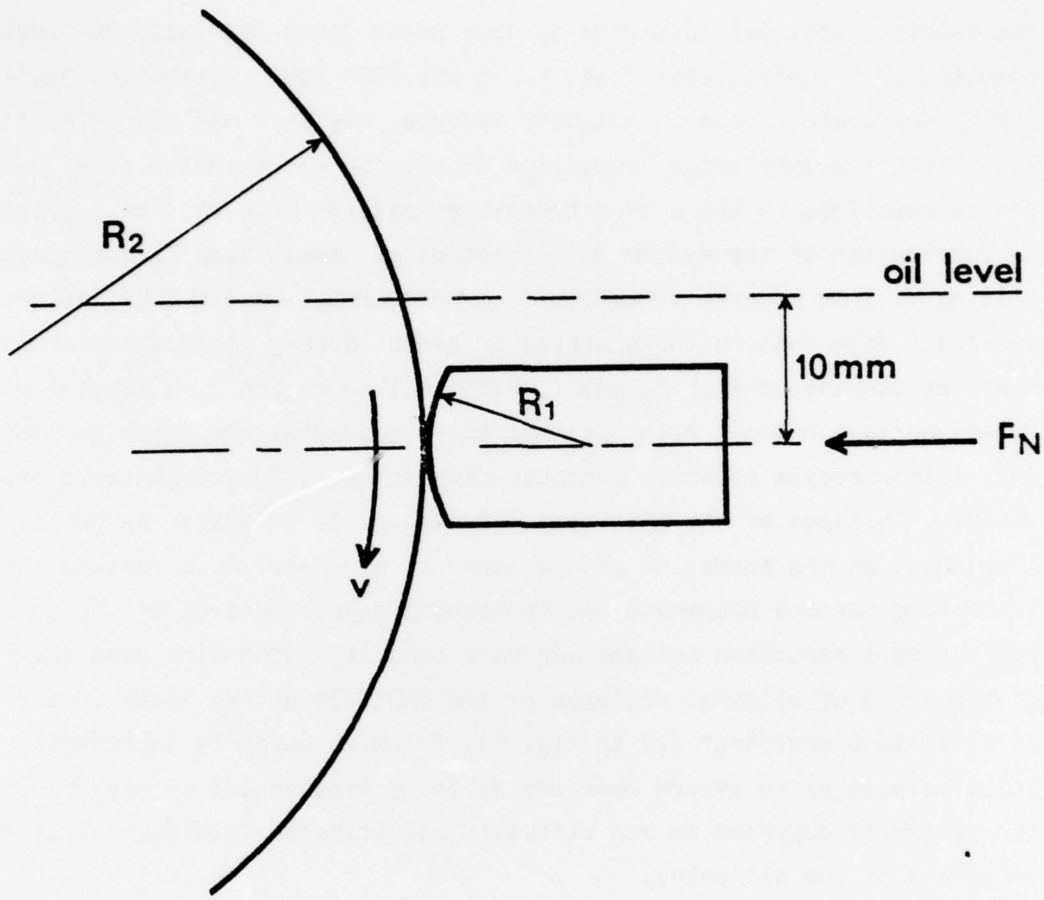


Fig. 2 Essential elements of pin and ring assembly

In the past conflicting evidence was put forward by different researchers with regard to the influence of composition, structure and hardness of the steel. For instance Niemann and Lechner (ref. 3) claimed that the load carrying capacity of gears decrease appreciably with increasing percentage of retained austenite. Similar results were put forward by Evans (ref. 4). On the contrary, Matveevsky et al (ref. 5) concluded from the results of four-ball machine tests that the amount of retained austenite had little or no effect upon the load carrying capacity. They found that addition of 1.6% of chromium to unalloyed steel resulted in a considerable increase in load carrying capacity, but a further increase in chromium content had no further influence. The relative unimportance of retained austenite was confirmed by Roberts (ref. 6), who found no direct relationship between retained austenite content and scuffing resistance.

In planning the present investigation it was reckoned with the possibility that the above apparent discrepancies in test results, produced by different authors, might well be attributable to differences in lubrication condition, prior to scuffing.

2. EXPERIMENTAL

As in previous work, the experiments were performed on a pin-and-ring test rig. Fig. 2 shows the essential data. Hemispherical pins with radii of curvature R_1 of 5 mm and polished surfaces were pressed against curved surfaces of rotating rings with radii of curvature R_2 of 38 mm and a surface roughness of 0.12 μm r.m.s. (prepared by grinding). The pins were loaded in the axial direction with forces in the range of 50 to 100 N and the rings rotated at speeds of 0.5, 1.0 and 2.0 m/s. The point of contact between the pin and the ring was located at about 10 mm below the oil level, so that there was ample supply of lubricant and lubricant starvation effects were completely avoided. The lubricant bath formed part of a thermostat system, by which the bulk temperature of the oil was kept constant at the experimental value of 60°C with an accuracy of 1°C. The force on the pin was applied by means of a pneumatic loading system and the friction between pin and ring was measured by means of strain gauges attached to a thin walled part of the driving shaft. The procedure for measuring the critical combinations of loading force and speed under which the different transitions occur was following: prior to loading, the speed of rotation of the ring was adjusted at the chosen value.

Next the load on the pin was applied in less than 0.1 sec. From the coefficient of friction and the specific wearrate during a 5 min test it could be concluded in which regime of lubrication the system operated (c.f. Fig. 1). The transition load F_{N_c} at a given speed v was found by performing a series of 5 min tests, each individual test starting with newly machined surfaces. In general, 4 to 6 tests sufficed for accurate determination of F_{N_c} (accuracy: ± 25 N).

As usual the experiments were performed in a reference lubricant, also used in previous testing, i.e. a marine diesel engine oil of narrow molucular cut. This oil had a dynamic viscosity $\eta = 6 \cdot 10^{-2}$ Ns/m^2 at 60^{o}C, a viscosity index of 59 and a P/N/A ratio of 52/40/8.

In the present case the pins and the rings were made from commerically available tool steels with chemical compositions as given in Table 1.

It can be seen that the steels differ primarily in chromium content, further the A2 and D2 steels contained Mo and V, while steel E 52100 did not.

Table 1

Chemical composition of tool steels (wt.%)

Type of steel	C	Si	Mn	Cr	Mo	V	Fe
AISI E 52100	1.00	0.25	0.30	1.50	-	-	bal.
AISI A2	1.00	0.30	0.50	5.20	1.00	0.20	bal.
AISI D2	1.55	0.30	0.30	12.00	0.70	1.00	bal.

From these materials the pins and rings were made by a turning process. After machining, the specimens were heat treated in a neutral heat treatment salt during 30 min (steel E 52100) or 45 min (steels A2 and D2); the heat treatment temperatures are given in Table 2. After heat treatment the specimens were quenched in oil of 50^{O}C, long enough to reach the oil temperature. For the medium and high percentages of retained austenite (R.A.%), the steels were finally tempered during 2 hours at 180^{O}C.
For the low R.A. percentages, the retained austenite, formed during heat treatment, was transformed by a sub-zero treatment in liquid nitrogen, followed by 2 hours tempering at 180^{O}C.
These treatments resulted in percentages of retained austenite of approx. 9 and 17 for steel E 52100 and approx. 24 and 55 for steels A2 and D2 (see Table 2).

Table 2

Treatment data, resulting amount of retained austenite and hardness of three different tool steels. Temper treatment: 2 h, 180^{O}C

Type of steel	Austenitizing temperature (^{O}C)	Amount of retained austenite		Vickers hardness HV*) (10^7 N/m^2)
		pin (%)	ring (%)	
AISI E 52100	850	2.0 ± 0.2	1.8 ± 0.2	800
	850	8.8 ± 1.0	10.9 ± 0.8	780
	900	17.2 ± 0.9	17.0 ± 1.2	770
AISI A2	950	4.4 ± 0.5	3.7 ± 0.5	810
	950	17.5 ± 1.4	22.4 ± 1.9	770
	1020	51.2 ± 2.2	60.3 ± 2.1	610
AISI D2	1040	3.5 ± 0.3	4.3 ± 1.8	~~770~~ 800
	1040	19.3 ± 2.7	22.8 ± 3.1	760
	1090	59.2 ± 2.6	54.5 ± 2.2	630

*) Load: 100 N

Table 2 further shows that at similar R.A. percentage the Vickers hardness of pins and rings is almost constant; thus it is independent of the chemical composition of the steel. The hardness is found to decrease with increasing R.A. percentage as shown in Fig. 3.

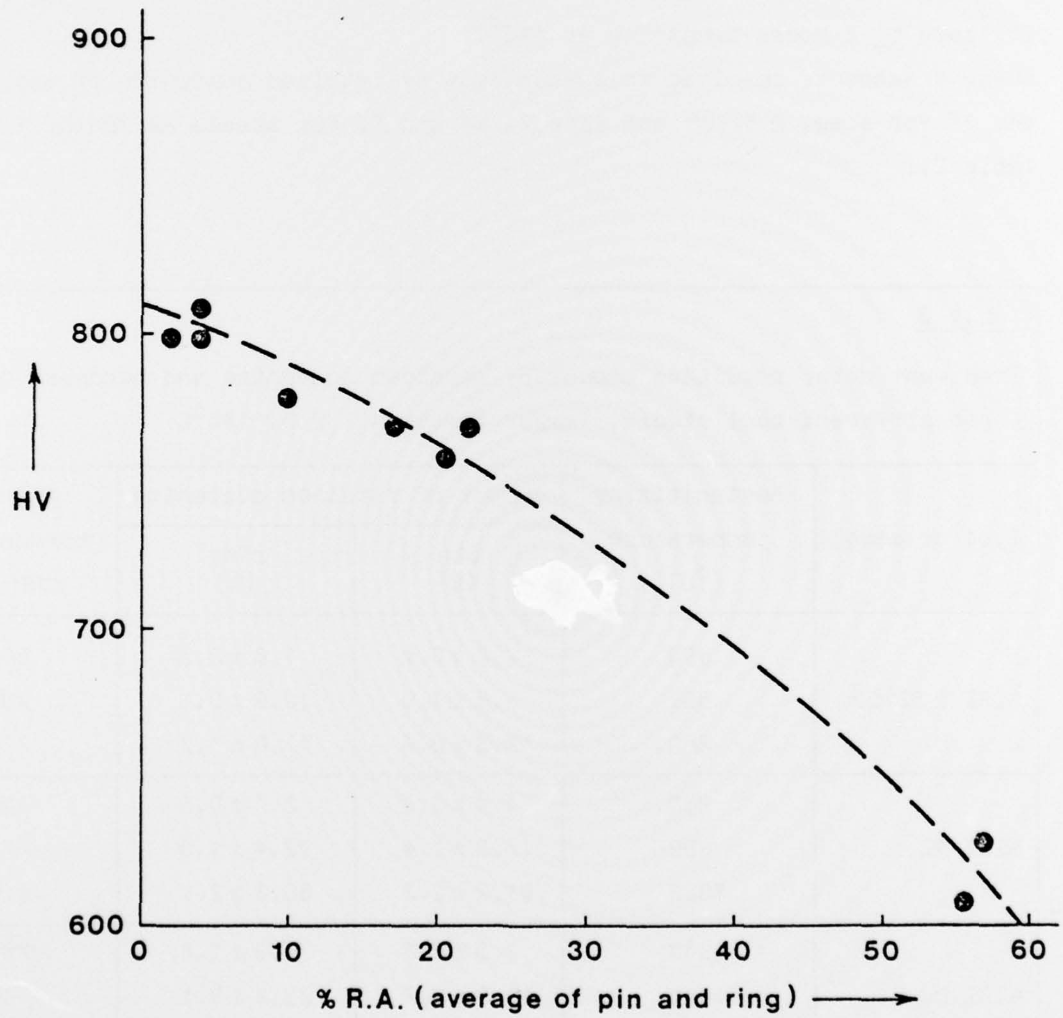


Fig. 3 Vickers hardness (HV) versus percentage of retained austenite (R.A.%) for steels AISI E 52100, A2 and D2.

Figs. 4, 5 and 6 show representative micrographs of the structures of the resulting materials. It can be seen that the volume percentage of precipitated carbides increases appreciably with increasing percentage of alloying elements. Further there is a tendency towards an increase in coarseness of the structure with increasing amount of retained austenite as caused by differences in heat treatment and procedure.

After heat treatment the specimens were ground to a surface roughness of approx. 0.12 r.m.s. Next the pins were polished by a specially designed procedure which yielded very smooth spherical surfaces with a finish, comparable to that of special quality ball-bearing balls (Fig. 7). It was established that - at least at light-microscopic level - grinding nor polishing affected the microstructure of the materials.

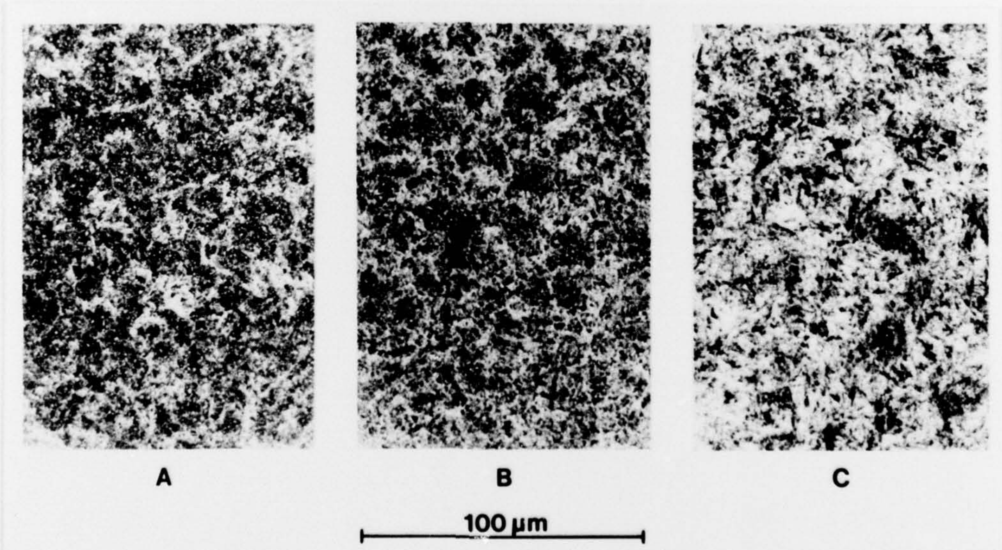


Fig. 4 Micro-structure of material AISI E 52100. Chromium content: 1.5%. Amount of retained austenite: 1.8% (A), 10.9% (B) and 17.0% (C).

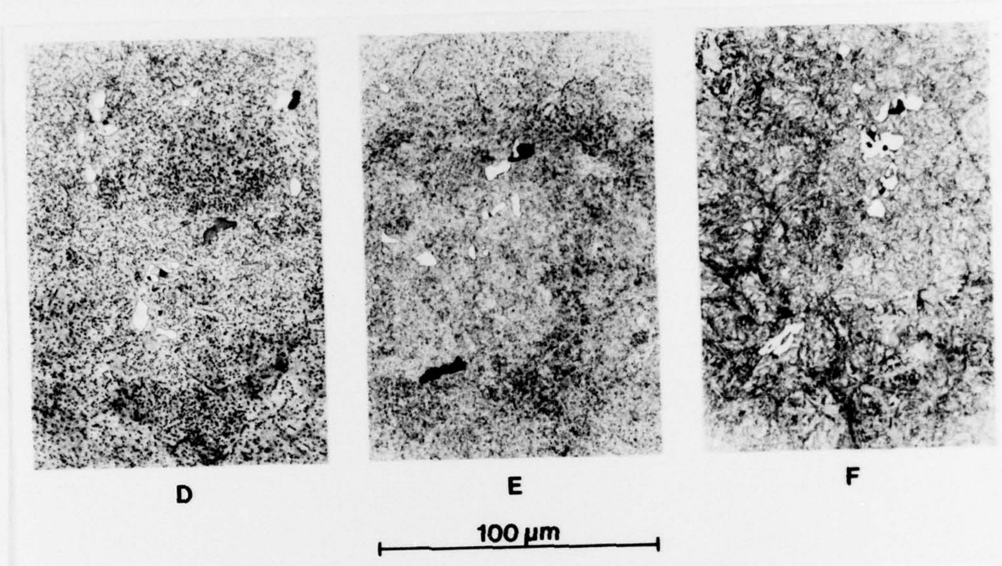


Fig. 5 Micro-structure of material AISI A2. Chromium content: 5.2%. Amount of retained austenite: 3.7% (D), 22.4% (E) and 60.3% (F).

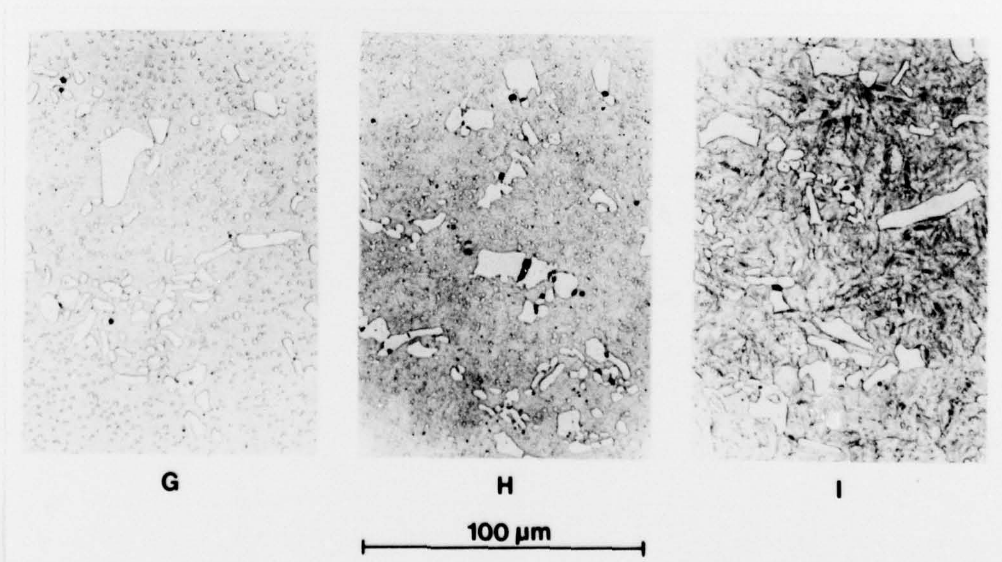
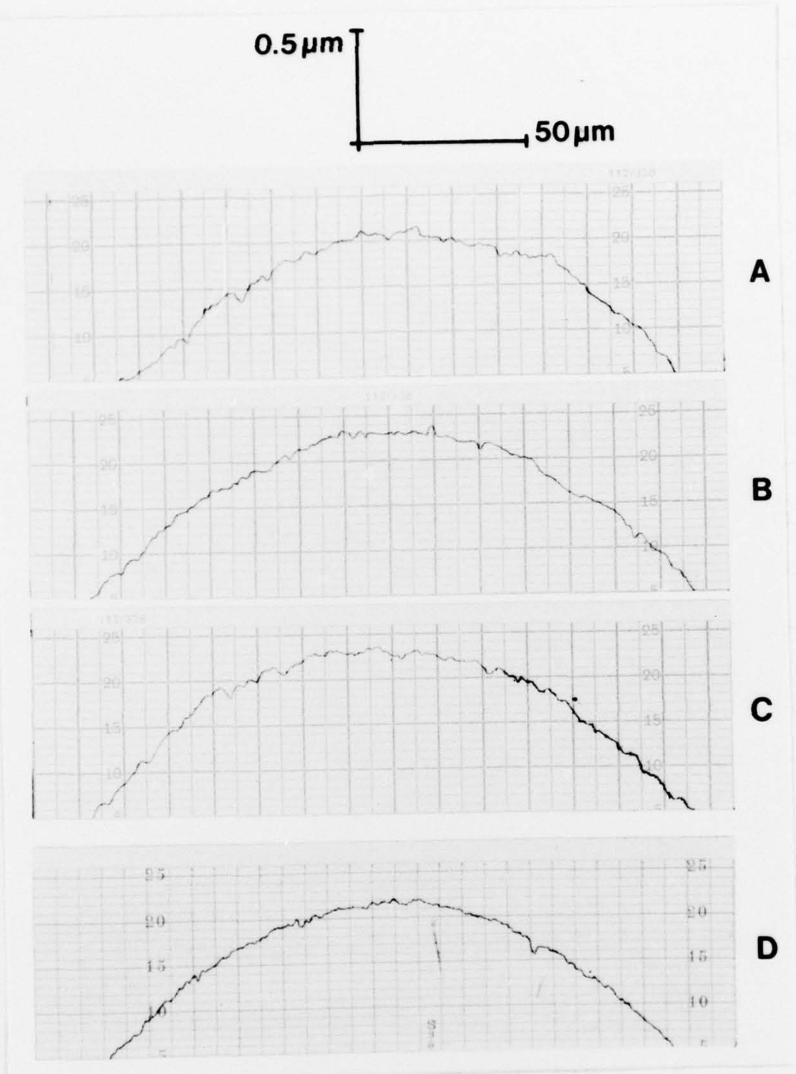


Fig. 6 Micro-structure of material AISI D2. Chromium content: 12.0%. Amount of retained austenite: 4.3% (G), 22.8% (H) and 54.5% (I).



<u>Fig. 7</u> Talysurf linetracings (at very high vertical magnification) of the spherical surface of pins made from material AISI A2 with 4% R.A. (A), 20% R.A. (B) and 55% R.A. (C) in comparison with a linetracing of a special quality SKF ball (D).

3. RESULTS AND DISCUSSION

Numerical results obtained with the different types of steel are shown in Table 3. On the basis of these data the transition diagrams shown in Fig. 8 were constructed.

It can be seen that the chemical composition of the steel has little or no effects upon the first and third primary transitions. On the other hand, it influences quite strongly the second primary transition (i.e. from the region of incipient scuffing to that of scuffing). In fact at v = 0.5 m/s the load carrying capacity decreases from about 500 N for steel E 52100 to about ~~175~~ 275 N for steels A2 and D2.

Table 3

Load carrying capacities at 0.5, 1.0 and 2.0 m/s

Steel			F_{N_c} (N) v = 0.5 m/s		F_{N_c} (N) v = 1 m/s		F_{N_c} (N) v = 2 m/s	
type	% R.A.	HV	$A_1 - S$ *) or $S - A_3$	$A_2 - S$	$A_1 - S$ or $S - A_3$	$A_2 - S$	$A_1 - S$ or $S - A_3$	$A_2 - S$
E 52100	2	800	150	525	125	225	100	-
	9	780	175	500	125	175	100	-
	17	770	175	475	125	150	100	-
A2	4	810	150	275	125	175	100	-
	20	770	175	250	125	-	100	-
	55	610	225	-	150	-	125	-
D2	4	800	150	275	125	-	100	-
	21	760	175	250	125	-	100	-
	55	630	225	-	175	-	150	-

*) See Fig. 1.

The influence of differences in heat treatment, quenching and tempering procedure, as manifest in R.A. percentage, coarseness of structure and hardness, is found to be of a dualistic nature. The load carrying capacity of the partial EHD film shows a weak tendency to increase and the load carrying capacity at the third primary transition shows a much stronger tendency to decrease with increasing R.A. percentage and, thus, with increasing coarseness and decreasing hardness.

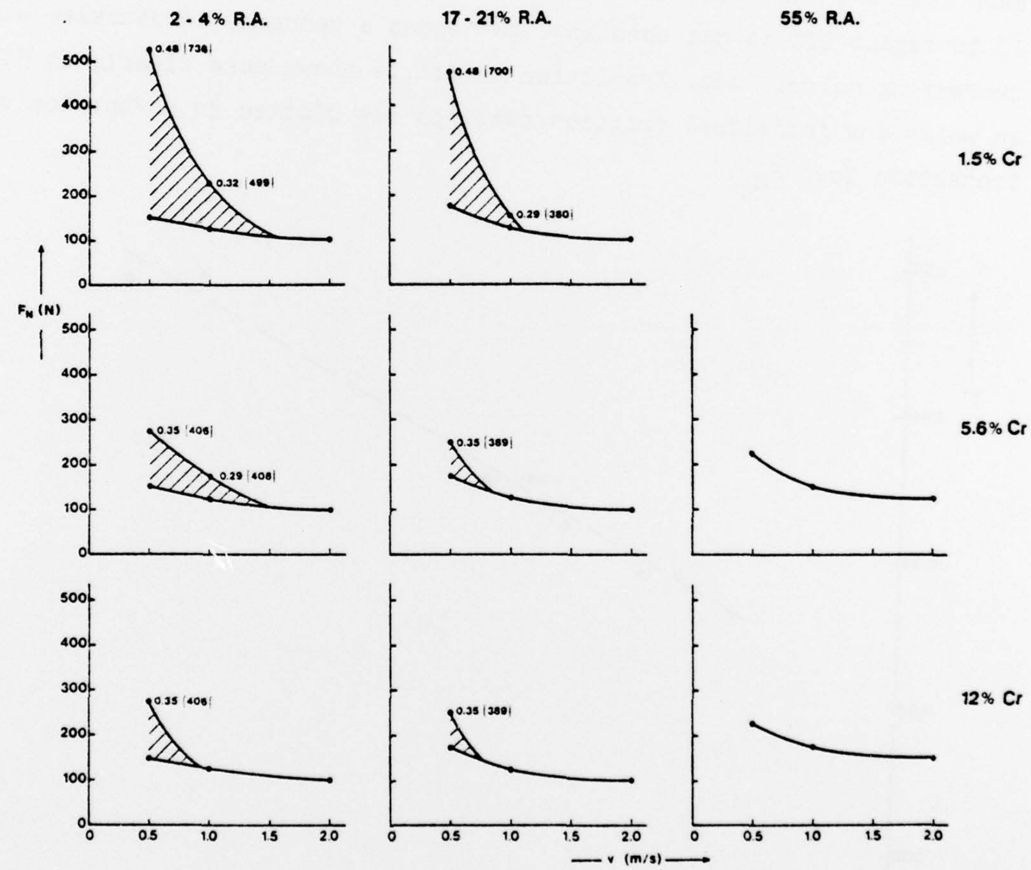


Fig. 8 Transition diagrams of the different tool steels, lubricated with marine diesel engine oil of 60°C. The figures denote f^* (coefficient of friction just below transition) and calculated conjunction temperature T_c (in brackets), respectively.

As a result of these effects, the importance of the regime of incipient scuffing (II in Fig. 1) decreases appreciably with increasing percentage of alloying elements as well as with increasing percentage of retained austenite (or increasing coarseness or decreasing hardness). This is borne out quite clearly by the diagrams, shown in Fig. 8.

In the diagrams of Fig. 8 the figures denote the coefficient of friction, measured directly below transition (f^*) and the calculated value of the maximum conjunction temperature (T_c). The latter was calculated according to Archard's modification of the Blok - Jaeger theory (ref. 7). It can be seen that the coefficient of friction, just prior to transition from region II to region III is not constant, but shows a tendency to decrease with decreasing normal load. The latter effect is shown more clearly in Fig. 8, in which the individual friction readings are plotted as a function of the transition load F_{N_c}.

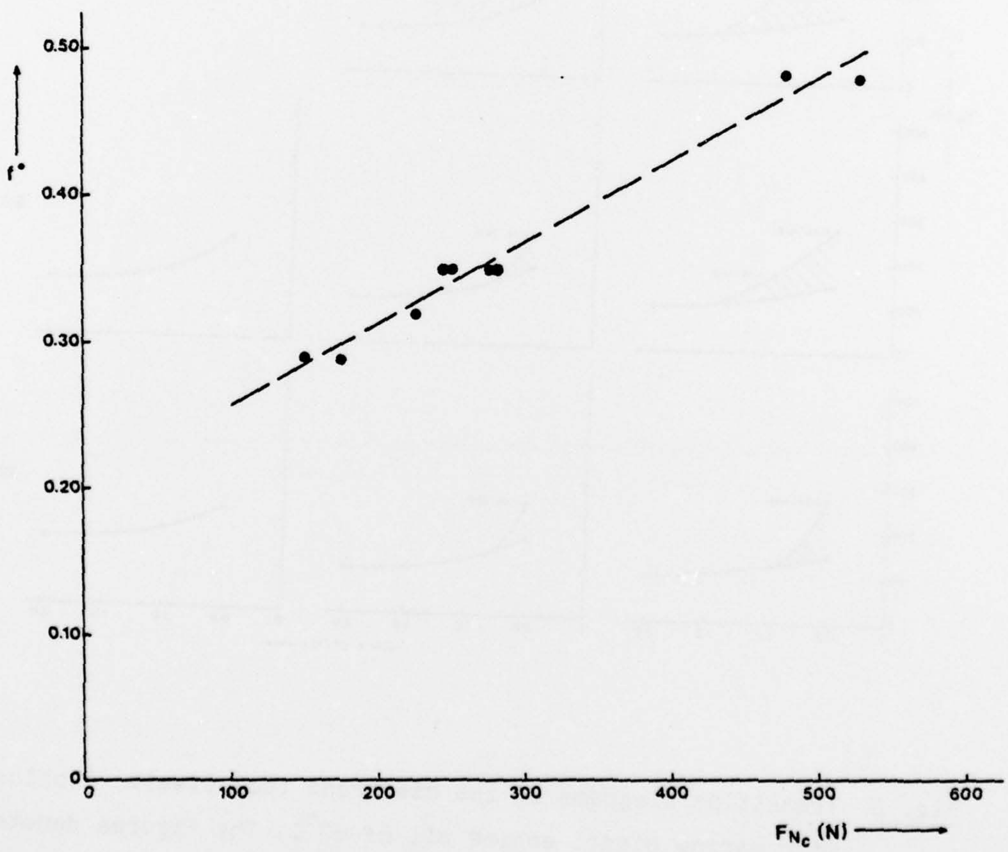


Fig. 9 Relation between coefficient of friction f^* and transition load F_{N_c}.

Fig. 9 also shows that the values of T_c, calculated for material E 52100, are not constant. This does not necessarily mean that the second primary transition does not depend upon the conjunction temperature. Actually, due to the grinding marks on the ring surface, the contact is disperse rather than homogeneous, which means that Archard's simplified equations do not really apply. Clearly this point deserves further attention.

4. COMPARISON WITH RESULTS, OBTAINED BY NIEMANN AND MATVEEVSKY

It is of interest to compare the present results on the effects of chemical composition and structure of the steel on load carrying capacity with results, presented by Niemann and Lechner (ref. 3) and Matveevsky et al. (5).

Niemann and Lechner did not present data on the structural conditions of the steels, used in their tests. Still a comparison with their results, which are summarized in Table 4, reveals some significant points.

Table 4

Results of Niemann and Lechner on retained austenite

DIN specification	Cr %	Ni %	Mn %	% retained austenite	"relative load carrying capacity" *)
18 Cr Ni 8	2.0	2.0	0.5	10	1.2
20 Mn Cr 5	1.2	-	1.3	20	1.0
14 Ni Cr 18	1.1	4.5	0.6	25	0 9
20 Mn Cr 5	1.2	-	1.3	30	0 7
X 25 Cr Ni Mn P 1810	18.0	10.0	3.5	100	0.4
X 8 Cr Ni 1212	12.0	13.0	2.0	100	0.2

*) Probably at second primary transition (A_2 - S)

Firstly it should be noted that - on the basis of the experimental conditions - it can be inferred that Niemann and Lechner studied the second primary transition (A_2 - S in Fig. 1).

Further Table 4 shows that the steels were by no means of constant chemical composition. Actually the results probably do not so much show an effect of retained austenite as well as a pronounced, unfavourable effect of alloying elements. This is in accordance with the present results.

In fact only the two versions of steel 20 Mn Cr 5 (second and fourth entry in Table 4) may serve to estimate the effect of retained austenite (and - probably - a coarser structure and a lower hardness). They show a decrease in load carrying capacity of some 30% at an increase from 20% R.A. to 30% R.A.

In the present study a similar effect (i.e. some 30% reduction in load carrying capacity) was found for steel E 52100 at v = 1 m/s and R.A. percentages of 2 and 17%, respectively.

As Niemann and Lechner's results probably concern the second primary transition, the beneficial effect of increased R.A. percentage (or increased coarseness or decreased hardness) as observed in the present study, was not observed by them.

Matveevsky et al. did not show data on the structural conditions of their steels either.

The results on the influence of chromium as found by these authors, were expressed in terms of a "critical temperature" for desorption of the lubricant. They are summarized in Table 5.

It can be seen that, in the range of chromium contents from 1.6 to 9.7%, the "critical temperature" was found to be virtually independent of the chromium percentage.

At the very low speed of rotation at which the experiments were performed (1 r.p.m. in the four-ball tester) the transition phenomena as observed by Matveevsky et al. most probably corresponded to the first primary transition in the present study (A_1 - S in Fig. 1). From Table 3 and Fig. 7 it can be

Table 5

Results of Matveevsky et al. on chromium percentage

Grade of steel[1]	chromium perc. at. %	critical temperature
Y 10	-	20
X 15	1.56	140
10 X 4.5	4.54	120
10 X 5.6	5.80	130
10 X 9.5	9.70	130

[1] Russian designation

seen that, as far as the influence of chromium content on the load carrying capacity of the partial EHD film is concerned, the present results fully corroborate those of Matveevsky et al. On the other hand, an increase in chromium content from 1.5 to 5.6% is found to have a most pronounced, unfavourable influence on the load carrying capacity at second primary transition (A_2 - S in Fig. 1). Clearly, this transition did not come into play in Matveevsky's tests.

5. PREDICTIVE POWER OF THE TRANSITION DIAGRAM

The present results bear out quite clearly that by applying a transition diagram as shown in Fig. 1, differences in load carrying capacity as caused by different steels can be identified easily. This can be a very useful function oriented characterization of materials for gears, cams and tappets, etc.

It is also shown that, by using the transition diagram, apparent controverses between different authors can be reconciled, as they can be attributed to differences in lubrication condition prior to scuffing.

6. CONCLUSIONS

1. In concentrated contact situations F_N-v-(T) transition diagrams form a useful tool in function oriented characterization of different lubricants and steels.

2. The percentage of alloying elements in tool steel does not influence the first and third primary transitions. On the other hand, the load carrying capacity at the second primary transition is found to decrease appreciably by increasing the chromium percentage from 1.5 to 5.6% (with the simultaneous addition of 1% Mo and 0.2% V).

3. The heat treatment, quenching and tempering procedure has a rather strong effect on the load carrying capacity at first and third primary transitions. On the other hand, an increase in percentage of retained austenite (with corresponding increase in coarseness and decrease in hardness) is found to cause a minor decrease in load carrying capacity at the second primary transition.

4. As a result of the effects, mentioned in conclusions 2 and 3, the importance of the regime of "incipient scuffing" decreases with increasing percentage of alloying elements and increasing percentage of retained austenite (or increasing coarseness or decreasing hardness).

5. The apparent discrepancies in the results, produced by different authors, regarding the effects of alloying elements and retained austenite, can probably be attributed to differences in lubrication condition, prior to scuffing.

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