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The Dry Wear of Steels I. The General Pattern of Behaviour

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THE DRY WEAR OF STEELS

I. THE GENERAL PATTERN OF BEHAVIOUR

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The broad trends of the wear rate when steels rub together without lubrication have been studied by means of pin and ring apparatus. Over a wide range of load (10 g to 40 Kg) and sliding speed (1·7 to 266 cm/s) the wear process at equilibrium is either of a severe type, producing coarse metallic debris, or of a mild type, producing fine oxidized debris. The corresponding wear rates differ by more than two orders of magnitude. Transitions from one wear process to the other occur at well-defined loads and for soft steels a basic pattern, comprising three transitions, has been identified: T_1, a change from mild wear to severe at light loads; T_2, a change from severe wear back to mild at higher loads; T_3, a minor change in the mild wear rate at loads above T_2, characterized by divergent wear rates of the pin and ring. The way in which this pattern varies with the sliding speed and with the composition and hardness of the steel is traced and the findings of previous investigations co-ordinated in the general framework.

1. Introduction

In view of the extremely important role of iron and steel in practical rubbing systems, it is not surprising that many types of laboratory and field test have been used to establish the manner in which the resistance to wear varies with composition, structure and hardness in all the diversity that characterizes ferrous metals. However, comparatively few investigations have surveyed a broad range of rubbing conditions and these have shown that, in critical circumstances, the whole character of the wear process changes abruptly when the rubbing conditions alter only slightly. The change in wear rate accompanying these transitions often completely overshadows differences associated with the composition or structural state of the materials.

A pronounced change in wear rate with sliding speed was observed by Kehl & Siebel (1939) during tests on high carbon steels and cast irons in the form of hollow cylinders, rubbed end on against like cylinders. They found that when the sliding speed exceeded a critical value (which differed appreciably for the various materials) the wear rate diminished by a factor of about 600. As shown by the results for one steel in figure 1, this transition occurred only when the steel was soft; the low-speed régime of rapid wear was not observed on samples quenched and tempered to high hardness values. No explanation for the phenomenon was advanced, though one possibility, that oxidation of the surfaces was affecting the wear rate, appeared to be precluded by the fact that the same change could be produced in an atmosphere of alcohol vapour.

Using a similar experimental technique, Kragelskii & Shvetsova (1955) observed a critical sliding speed for soft steel (0·8 % C); hardened steel again gave low wear at all

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speeds. The low wear rate was associated with fine oxidized debris and the high wear rate with coarse metallic fragments. Critical sliding speeds, associated with falls in wear rate of varying magnitude, were also observed with certain non-ferrous metals, and the results were interpreted collectively in terms of thermal softening. It was postulated that the critical sliding speed represents a value at which the frictional temperatures are great enough to soften the points of contact and that this softening localizes the damage, thereby reducing the wear rate.

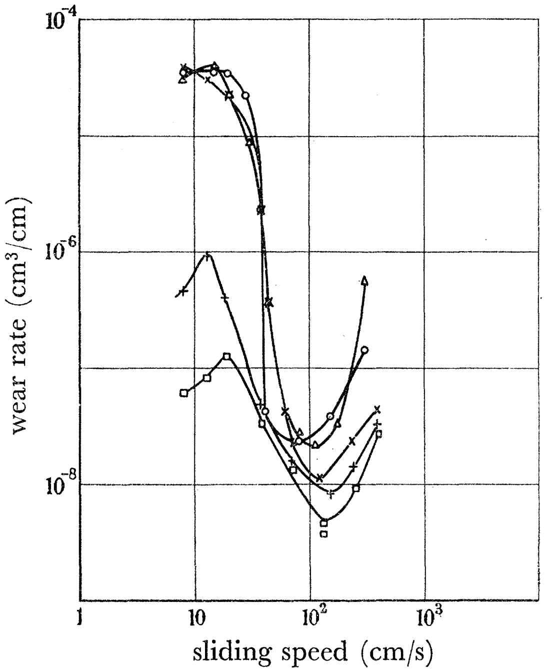

FIGURE 1. Influence of speed on wear rate of 0·64 %C steel, after Kehl & Siebel (1939). Load 30 Kg. Hardness (V.p.n.): ×, 160; ○, 178; △, 348; +, 445; □, 690.

Kragelskii & Shvetsova noted briefly that when the critical speed was exceeded, there was always some delay before the transition from the severe to mild form of wear took place. This observation provides a link with findings of the present author. In tests with pins of soft, plain carbon steels (0·12 to 0·78 % C) rubbing on rings of like material, a similar change in the character of the wear process was observed (Welsh 1957). At constant load and speed a transitory stage of severe wear was followed by indefinitely prolonged mild wear. The transition occurred more rapidly as the carbon content of the steel increased and was also accelerated by an increase of load or speed. Micro-hardness measurements on the tracks in the mild-wear state showed that pronounced hardening (up to 900 Vickers pyramid number (V.p.n.)) had occurred and the transition in the wear rate was accordingly interpreted as the result of surface hardening produced by frictional heating of the points of contact, i.e. a self-induced quench-hardening process. On this basis it was possible to predict that for each steel there should be critical values of load and speed below which continuous severe wear would be encountered and above which a primary stage of severe wear would change to steady mild wear. Archard (1959) subsequently studied the behaviour of one of the steels (0·52 % C) in greater detail and established critical speeds for two loads. He showed, furthermore, that the theoretical surface temperatures corresponding to these loads and speeds were great enough to induce the α-γ transformation in the steel and promote quench-hardening.

There can be little doubt that the transitions observed by Kehl & Siebel (1939) and Kragelskii & Shvetsova (1955) on the one hand and by Welsh (1957) and Archard (1959) on the other, represent the same phenomenon, though the two interpretations of surface softening and surface hardening could not be more radically opposed.

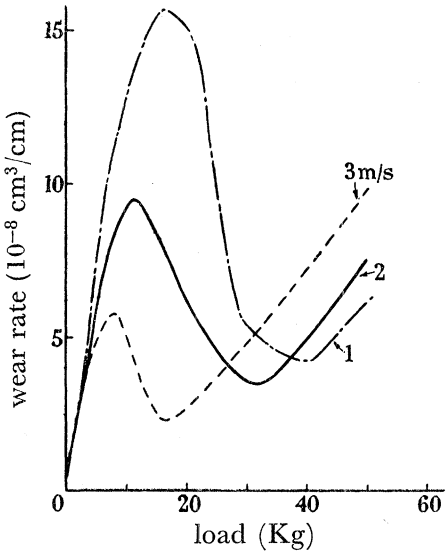

FIGURE 2. Wear rate plotted against load for soft iron pins on hard steel disks, after Mailänder & Dies (1943).

The differing behaviour of soft and hard steels noted by Kehl & Siebel (1939) and Kragelskii & Shvetsova (1955) appears to reflect certain findings of Rosenberg & Jordan (1934) who studied the wear of three steels (0·43, 0·81 and 1·26% C) in the form of disks rotated in line contact. When tested in air the wear rates of these steels were invariably low and the worn surfaces were smooth and covered with oxide films. When tested in nitrogen or hydrogen atmospheres, however, two types of behaviour were observed. Steels hardened and subsequently tempered at low temperatures again gave low-wear rates and smooth, oxide-covered surfaces, but after tempering at higher temperatures wear was very rapid and the surfaces were rough and bright. The high- and low-wear states resemble, both qualitatively and quantitatively, those already described, but the implication that the high-wear rate does not develop in air introduces a discordant feature. Rosenberg & Jordan assumed that the oxide film which forms on the surface while rubbing in air is able to prevent severe wear of steel of any hardness, while the comparatively thin layer formed in nominally oxygen-free atmospheres is protective only when the substrate hardness is sufficiently high.

A transition of much smaller magnitude was observed by Mailänder & Dies (1943) during a study of the wear of soft iron pins on hard chrome steel disks. In most circumstances the graphs of wear rate against load showed an inflexion, representing a three- to fivefold drop in wear rate (see figure 2), though the position and shape of the curves were strongly influenced by the nature of the atmosphere. In the region of the minimum wear rate, hard patches had formed on the pin surfaces and the authors suggested that the transition might be associated with this surface hardness, though the profound effects of the atmosphere could not be explained in definite terms. Kauzlerich, Hagglund & Modrak (1961) have recently detected a similar inflexion in the wear rate–load graph of fully hardened 0·4 % C steel pins rubbed in air on rings of like material. A significant change in surface hardness was not observed in these circumstances and a novel explanation for the change in wear rate was advanced. It was postulated that the transient temperatures at the rubbing surface induce temper-brittleness in the steel and that this brittleness allows welds between the points of contact to break at or closer to the junction than would otherwise be the case, resulting in a lower wear rate.

Summarizing, two broad types of transition have been reported for dry-rubbed steels: (1) A change from a severe to a mild form of wear involving a reduction in wear rate of up to 1000-fold. This change has been observed on soft steel/soft steel combinations with increase of sliding distance, speed or load on specimens rubbed in air and with increase in the hardness of the steel for surfaces rubbed in hydrogen or nitrogen. (2) A comparatively small change in the rate of wear (three- to fivefold) with increase of load. This transition involves no definite change in the character of the wear process and has been observed with soft steel on hard steel in air and various gases, and with hard steel on hard steel in air. Type 1 transition has been interpreted as a consequence of surface hardening, softening or oxidation and type 2 as the result of surface hardening or temper-brittleness.

The picture is obviously confusing. If the diverse and conflicting hypotheses are ignored, it is still difficult to place the phenomena in perspective or, when the whole gamut of variables is considered, to predict the circumstances in which one or the other type of transition might be expected to occur.

The present work was undertaken in the hope that by studying the behaviour of a group of steels in broad outline a general pattern would emerge, providing a firm basis for more detailed studies of particular facets of the pattern. In part I of this paper it is shown that the wear behaviour does change in a systematic fashion with load, sliding speed and composition and hardness of the steel, though the pattern established has proved to be more complex than originally envisaged. In part II the main aspects of the pattern are reviewed in the light of experiments designed specifically to interpret the phenomena encountered.

2. Experimental

(a) *Apparatus*

The wear rates were measured with apparatus of pin and ring type as used by the author (1957) and by Archard (1959) in earlier investigations. The basic features of this apparatus are a rotating shaft which carries the ring test piece (a cylinder, 2·54 cm diameter × 2·54 cm, 1·27 cm bore) and a freely moving loading arm on which the pin (0·635 cm diameter × 2·54 cm) is mounted. The ring is rotated by an electric motor, operating through a pulley system to give the appropriate shaft speed.

The pin was mounted in the crossed-cylinders arrangement shown in figure 3. This arrangement had the advantage that very small amounts of pin wear could be assessed by measuring the length of the wear scar and computing the volume, a feature which was

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

invaluable at the lowest loads when the weight changes were often too small to be determined with a normal chemical balance. The pin was clamped in a brass block which could be removed from the loading arm for measurement and then re-located accurately, i.e. without altering the position of the pin on the ring track.

Two pin and ring machines were used. Machine *A*, designed for a very wide range of loads and speeds, was employed for most of the tests but owing to the large number of measurements required it was at times expedient to conduct parallel tests on a second, less versatile machine *B*. As the results obtained with the two machines were not identical in every respect, all comparative tests were conducted on the same machine; when machine *B* was used this will be indicated on the appropriate graphs.

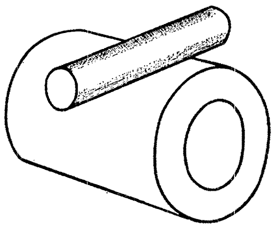

FIGURE 3. Crossed-cylinders arrangement of pin and ring.

(*b*) *Materials*

Analyses of the steels employed are shown in table 1. The plain carbon steels were selected to maintain, as closely as possible, constant proportions of manganese and silicon. Unless otherwise specified, the results apply to the condition in which the steels were received, i.e. hot-rolled or normalized. In all tests the pin and ring were of like material.

Before testing, the machined samples were ground with 600 emery paper to provide a standard finish and degreased with petroleum ether.

TABLE 1. ANALYSES OF STEELS USED

B.I.S.R.A. code	% C	% Ni	% Cr	% Mo	% Mn	% Si	% S	% P	condition
AL	0·026*†	0·038	0·01	0·01	0·05	0·02	0·035	0·004	hot-rolled
BB	0·12*	0·09	0·06	0·05	0·695	0·22	0·054	0·039	hot-rolled
CB	0·34*	0·08	0·07	0·05	0·755	0·297	0·045	0·037	hot-rolled
CA	0·52*	0·10	0·10	0·05	0·81	0·26	0·048	0·045	hot-rolled
CN	0·63*	0·13	0·05	0·05	0·87	0·24	0·048	0·040	normalized
CJ	0·78*	0·07	0·04	0·05	0·63	0·18	0·044	0·035	hot-rolled
DA	0·985*	0·12	0·07	0·05	0·64	0·228	0·05	0·032	hot-rolled
KN	0·33*	3·47	0·07	—	0·74	0·23	0·027	0·031	hot-rolled
GA	0·315*	0·073	1·09	0·012	0·69	0·20	0·036	0·039	hot-rolled
	0·33	0·22	3·2	0·42	0·50	0·25	0·009	0·013	hot-rolled

* Supplied by courtesy of B.I.S.R.A. † Armco iron.

3. PATTERNS OF WEAR

The author's earlier work (Welsh 1957) had indicated that for each steel, sliding at constant speed, there should be some critical value of load at which the equilibrium form of wear would change from severe to mild. The present experiments confirmed this prediction but a new feature soon emerged. A second critical load was detected, below which mild wear again prevailed. This trend is illustrated in figure 4 which shows the change of equilibrium wear rate with load for the 0·52 % C steel, sliding at a speed of 100 cm/s. In these experiments the full load was applied immediately; unless otherwise stated the same procedure was used throughout.

The first mild wear régime occurs in the range of load up to about 100 g. Between 100 and 200 g the wear rate increases by two orders of magnitude and remains at this high level over the load range up to 5 Kg. Between 5 and 6 Kg the wear rate falls abruptly and mild wear persists up to the maximum load employed (25 Kg).

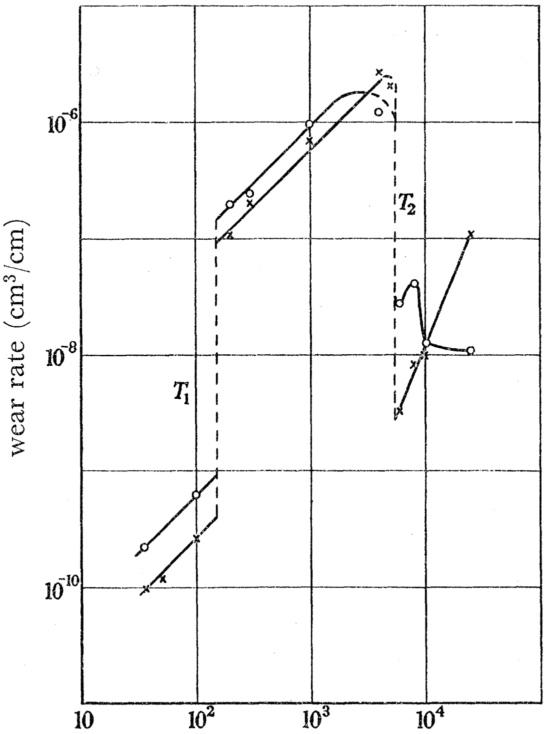

FIGURE 4. Wear rate plotted against load for the 0·52 % C steel. Sliding speed 100 cm/s. ×, Pin; ○, ring.

The transitions from mild to severe wear at low loads and from severe to mild wear at high loads will be designated T_1 and T_2, respectively. There was no obvious difference in the nature of the mild-wear processes below T_1 and above T_2. In both régimes the ring tracks were dark in appearance owing to the presence of adhering oxide and the debris was finely divided and highly oxidized, contrasting strongly with the bright, rough surfaces and coarse metallic debris produced in the range of severe wear. Again, in both régimes mild wear only developed after a primary stage of severe wear. It must, however, be remarked that whereas the severe wear stage at loads above T_2 was always definite and sometimes very prolonged, mild wear often developed very rapidly in the low load range and the severe wear stage was not always easy to discern. The behaviour at the lightest loads was not, in fact, entirely reproducible; in repetitive runs the severe wear stage was sometimes pronounced and sometimes not.

It will be noted that in the range below T_1 the pin and ring wear rates follow a similar course and that, within the limits of experimental error, the slope of the logarithmic plot is unity, i.e. the wear rate is proportional to load. The same is true of the severe wear range between T_1 and T_2. Above T_2, however, the pin and ring wear rates deviate quite markedly. The pin results appear to lie on a straight line which rises with a slope much greater than unity, while the ring wear rates follow an irregular course, rising at first with load then falling sharply. This disparity between the pin and ring results at loads above T_2 is important and will be reviewed in detail later, but in tracing the broad pattern of events it will be convenient to consider only the wear rates of the pin.

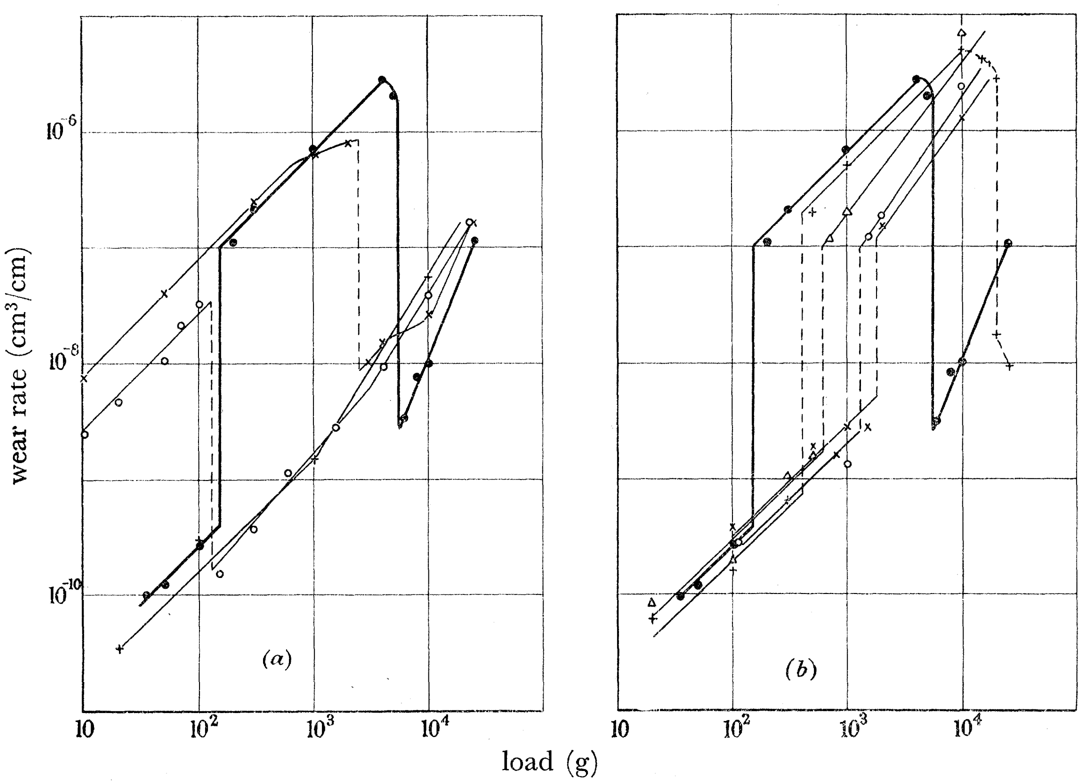

FIGURE 5. Effect of sliding speed on wear rate–load graph for the 0·52 % C steel: (*a*) increased speed, (*b*) decreased speed relative to figure 4 (reproduced in bold lines). (*a*) Sliding speeds (cm/s): ●, 100; ×, 133; ○, 200; +, 266. (*b*) Sliding speeds (cm/s): ×, 1·7; ○, 6·7; △, 33; +, 67; ●, 100.

(*a*) *Influence of speed*

The results in figure 4 were selected specifically to portray the co-existence of the two transitions. However, the values of the transition loads were strongly affected by sliding speed and at many speeds only one transition was encountered, as illustrated in figure 5. For clarity the results are split into two groups which illustrate the effect of (*a*) increased speed, and (*b*) decreased speed relative to figure 4 which is reproduced in each instance as a bold line.

It is apparent from figure 5 (*a*) that an increase in speed displaces both T_1 and T_2 to lower loads. A change from 100 cm/s to 133 cm/s has displaced T_1 beyond the minimum load (10 g) and T_2 likewise moves across and out of the graph as the speed is further increased to 200 and 266 cm/s; at the latter speed mild wear occurs over the whole load range. Conversely, a decrease in speed (figure 5 (*b*)) displaces both transitions to higher loads and at speeds less than 67 cm/s T_2 has passed beyond the maximum load employed.

At the lowest speed (1·7 cm/s), however, T_1 is still less than 2 Kg and it therefore seems improbable that this transition could be eliminated from the graph by decreasing the sliding speed further.

The influence of sliding speed on the transition loads is shown directly by the plot of figure 6. It is now apparent that T_2 changes much more rapidly with speed than does T_1. This graph provides in a convenient fashion the means for predicting the wear behaviour. A combination of load and speed lying within the two transition curves, i.e. in the hatched area of the graph, will give continuous severe wear and any combination outside this area will give mild wear (following a primary stage of severe wear).

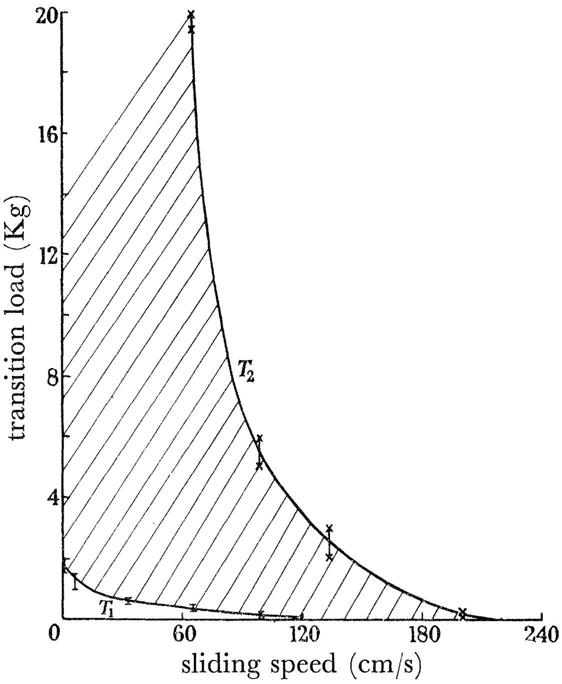

FIGURE 6. Change of transition loads with sliding speed, 0·52 % C steel.

(b) *Influence of carbon content*

Wear rate–load curves for steels ranging from 0·026 to 0·985 % C at a sliding speed of 100 cm/s are shown in figure 7. The curve for the 0·52 % C steel, already illustrated in figure 4, is reproduced in bold lines. Relative to this curve, as the carbon content is reduced T_1 is displaced to lower loads and T_2 to higher loads and for the lowest carbon content (Armco iron, 0·026 % C) severe wear occurs over the whole range. Conversely, an increase of carbon content rapidly narrows the range of severe wear and for the two highest carbon steels, 0·78 and 0·985 %, this range has been eliminated. It will, however, be noted that the curves for these steels show a definite inflexion at a load of several kilograms. A similar, but even more pronounced, inflexion is apparent on the curve for the 0·63 % C steel in addition to the normal T_2 transition, and it is therefore impossible to infer, as might otherwise be done, that the inflexion on the 0·78 % and 0·985 % curves is a vestige of the T_2 transition. This introduces an important feature which will be referred to again later.

Figure 8 shows a similar set of curves for a higher sliding speed (200 cm/s). At this speed none of the steels show the T_1 transition and all the T_2 transitions have moved to lower

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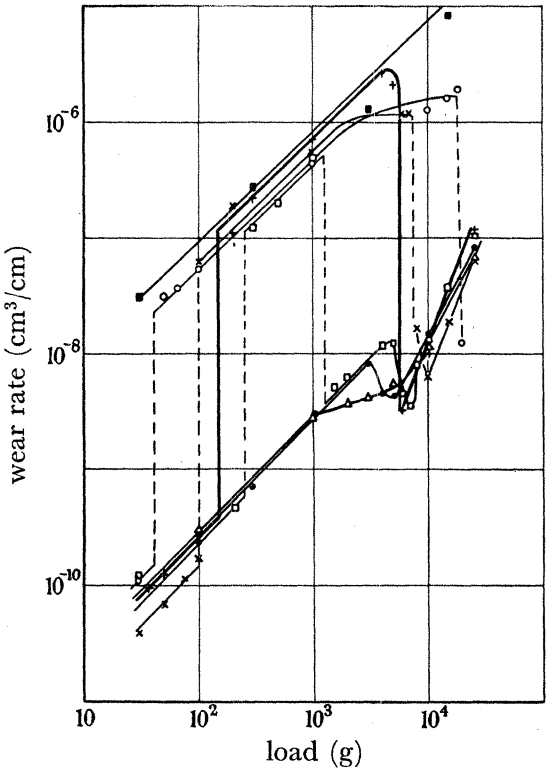

FIGURE 7. Wear rate plotted against load for various steels. Sliding speed 100 cm/s. Percentage carbon: ■, 0·026; ○, 0·12; ×, 0·34; +, 0·52; □, 0·63; ●, 0·78; △, 0·98.

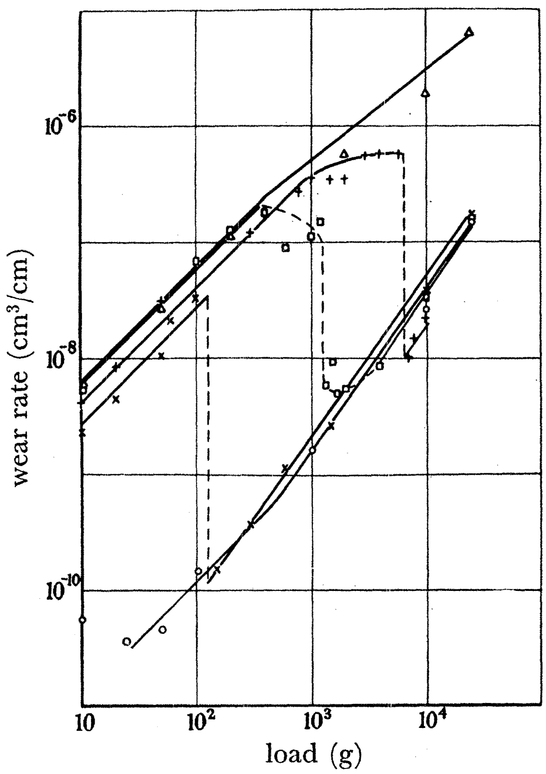

FIGURE 8. Wear rate plotted against load for various steels. Sliding speed 200 cm/s. Percentage carbon: △, 0·026; +, 0·12; □, 0·34; ×, 0·52; ○, 0·78.

loads. It will, however, be noted that the lowest carbon steel (0·026 %) still does not show the T_2 transition. Experiments with this steel at speeds up to 400 cm/s and loads up to 40 Kg failed to invoke the transition. Higher speeds and loads were not attempted as the temperature of the specimens (especially of the pin) increased extremely rapidly in such circumstances. On the other hand, the T_1 transition has been detected at low loads and sliding speeds (e.g. 0·5 to 1 Kg at 20 cm/s); the low carbon content does not actually preclude the mild-wear state.

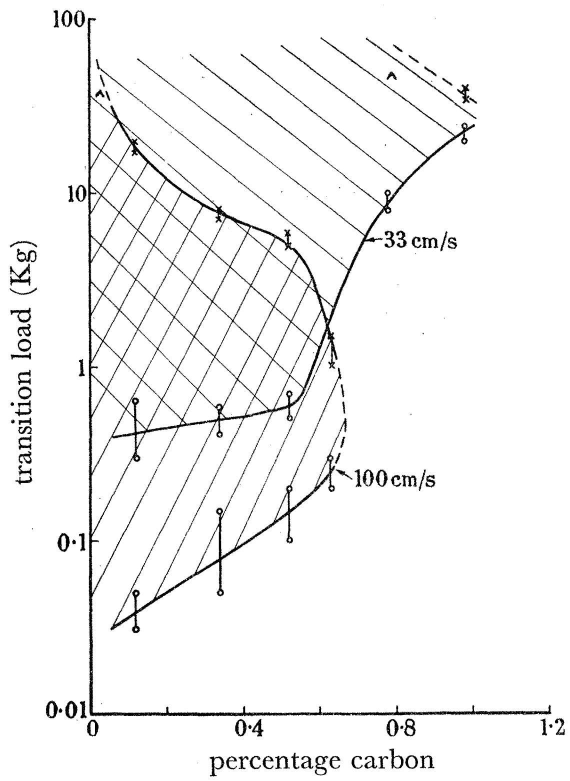

FIGURE 9. Variation of the range of severe wear (hatched) with carbon content and speed. ⚲, T_1; ⚳, T_2.

Figure 9 illustrates the way in which the range of severe wear is constricted as the carbon content increases. Results are shown for two sliding speeds. At 100 cm/s, T_1 and T_2 merge together at some carbon content between 0·63 and 0·78 % (see the wear rate–load graphs in figure 7) and for higher carbon contents mild wear is the equilibrium form of wear at all loads. At the lower sliding speed (33 cm/s), however, the range of severe wear extends to carbon contents exceeding 0·98 %. It will subsequently become apparent that the form of these curves is to some extent a function of hardness and in this respect the very high level of the T_1 values for the 0·78 % C and 0·98 % C steels should be specially noted.

(c) *Effect of hardening and tempering*

The results of tests on quenched and tempered samples of the 0·52 % C steel are shown in figure 10. With as-quenched samples (855 V.p.n.) mild wear occurs over the whole load range and at all but the highest loads the wear rate–load curve is linear with a slope of unity. Similar curves (not shown in figure 10) were obtained with samples tempered at temperatures up to 400 °C. The first appreciable deviation occurs after tempering at 500 °C when the hardness has fallen to 436 V.p.n.; the curve now shows a slight inflexion in the range 750 to 1000 g. Further tempering to 360 V.p.n. has produced a steep hump in the curve. (The wear debris in this region contained an unusual proportion of coarse metallic fragments and it is probable that the hump represents a mixed wear process with a bias towards mild wear.) On softening to 348 V.p.n. the curve resumes the form characteristic of unhardened steel and further softening to 286 V.p.n. expands the severe wear range by depressing T_1 and elevating T_2. The lowest hardness value, 219 V.p.n., was produced by furnace cooling the steel from 900 °C; the effect was to depress T_1 below the minimum load examined (50 g) but T_2 was not further changed.

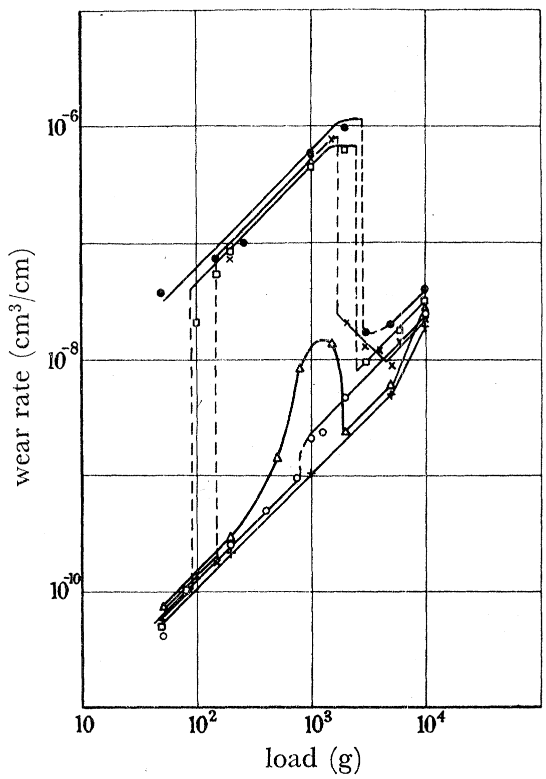

FIGURE 10. Effect of heat treatment on the wear rate pattern for the 0·52 % C steel. Sliding speed 100 cm/s. +, quench-hardened, 855 V.p.n.; ○, tempered at 500 °C, 436 V.p.n.; △, tempered at 550 °C, 360 V.p.n.; ×, tempered at 600 °C, 348 V.p.n.; □, tempered at 680 °C, 286 V.p.n.; ●, annealed, 219 V.p.n. (Machine B.)

Thus the pattern changes from one characteristic of soft steel to one characteristic of hard steel when the hardness is varied over a narrow interval. If the ambiguous result observed at 360 V.p.n. is ignored, the critical hardness must lie within the limits 348 to 436 V.p.n.

Equivalent tests on quenched and tempered 0·34 % C steel gave almost identical limits for the critical hardness, namely 343 to 433 V.p.n. However, this is not a constant value for all steels as revealed by figure 11 for the 0·12 % C steel. Hardening this steel to the maximum value (457 V.p.n.) attainable by water quenching has elevated T_1 and reduced T_2 but the severe wear range is still extensive. The critical hardness must therefore exceed

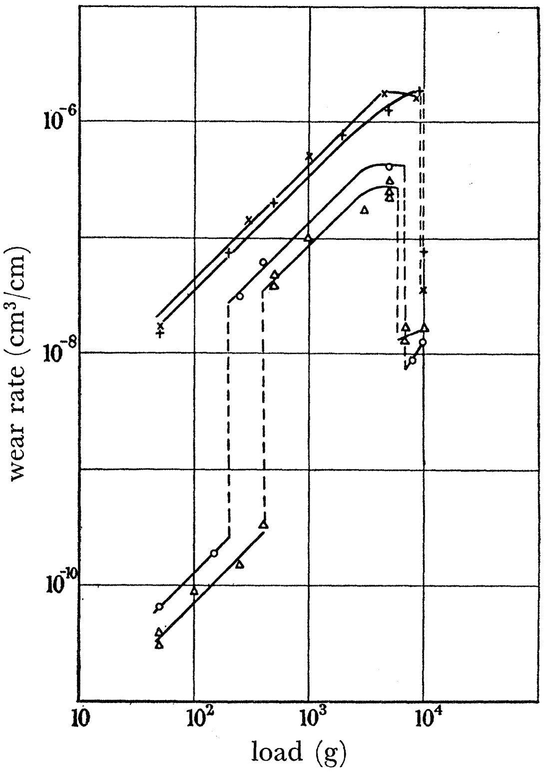

FIGURE 11. Effect of heat treatment on the wear rate pattern for the 0·12 % C steel. Sliding speed 100 cm/s. △, quench-hardened, 457 V.p.n.; ○, tempered at 180 °C, 359 V.p.n.; ×, hot rolled, 141 V.p.n.; +, annealed, 130 V.p.n. (Machine B.)

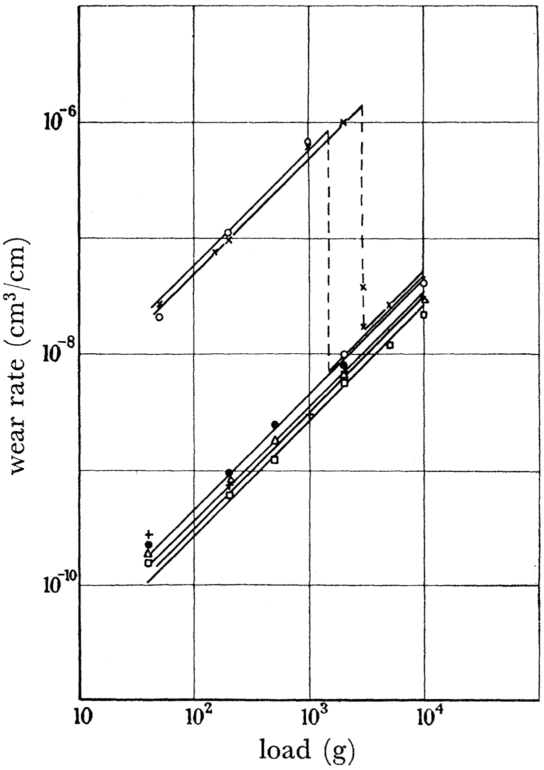

FIGURE 12. Effect of varying the ring hardness on wear rate–load graphs for the 0·52 % C steel. Sliding speed 100 cm/s. Pin, 217 V.p.n. Ring hardness (V.p.n.): ×, 243; ○, 360; +, 424; ●, 445; △, 472; □, 502. (Machine B.)

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

457 V.p.n. which lies significantly above the limits identified for the 0·34 and 0·52% C steels (see also the results for annealed high carbon steels below).

An additional aspect of the influence of hardness is introduced by figure 12. This graph shows the effect of varying the ring hardness while maintaining a constant pin hardness (217 V.p.n.). At some hardness between 360 and 424 V.p.n. the wear behaviour changes from the soft pattern to the hard. Similar limits were observed for this steel when the hardness of both members was varied (348 to 436 V.p.n.). This finding is of special interest when it is recalled that wear measurements are frequently conducted with the test sample rubbing on a disk or cylinder of hard steel. The present results imply that so long as the hardness of the disk or cylinder exceeds a critical, fairly low, hardness value, only the mild form of wear will be encountered.

(*d*) *Effect of annealing*

Comparative tests on low and medium carbon steels in the hot-rolled and annealed conditions showed little difference in behaviour (see figure 11) but a striking effect was observed when the higher carbon steels were annealed. These experiments were carried out to resolve a special issue. The results for quenched and tempered low and medium carbon steels had shown that within a certain range a small change of hardness can drastically alter the curve of wear rate against load. In the hot-rolled state the hardnesses of the 0·78 and 0·98% C steels were 278 and 319 V.p.n., respectively, values which were high enough to raise the suspicion that the behaviour of these steels might be governed more by hardness than by carbon content.

Figure 13 shows the effect of annealing the 0·78% C steel. For later reference both pin and ring results are presented but, to avoid confusion, the ring results are plotted separately. By varying the rate of cooling from the annealing temperature (850 °C) two hardness levels, 258 and 198 V.p.n., were achieved. Whereas, at this sliding speed, the hot-rolled steel gave mild wear at all loads, softening to 258 V.p.n. has produced a short, but definite, range of severe wear and further softening to 198 V.p.n. has greatly extended this range. It will be noted that the inflexion in the pin curve for the as-rolled steel is reproduced on the annealed steels but moves to higher loads with decreased hardness.

Figure 14 shows a similar result for the 0·98% C steel softened to 216 V.p.n. In the hot-rolled condition a severe wear range could only be produced on this steel at much lower speeds and higher loads (see figure 9). The general form of the curve after annealing is similar to that for the annealed 0·78% C steel, though the inflexion in the pin curve above T_2 is less pronounced.

It is clear that the behaviour of the hot-rolled high carbon steels is strongly dependent on the hardness. By analogy with the results for quenched and tempered steels, the critical hardness for the 0·78% C steel lies between the narrow limits 258 to 278 V.p.n. and for the 0·98% C steel between 216 and 319 V.p.n. It should be noted that, strictly, these limits apply only to the relevant sliding speed (100 cm/s). The fact that a severe wear range could be induced on these steels in the hot-rolled condition if the sliding speed was reduced sufficiently, implies that the critical hardness varies somewhat with speed. Since the pattern changes so rapidly with hardness, however, the influence of speed on the critical value need only be slight.

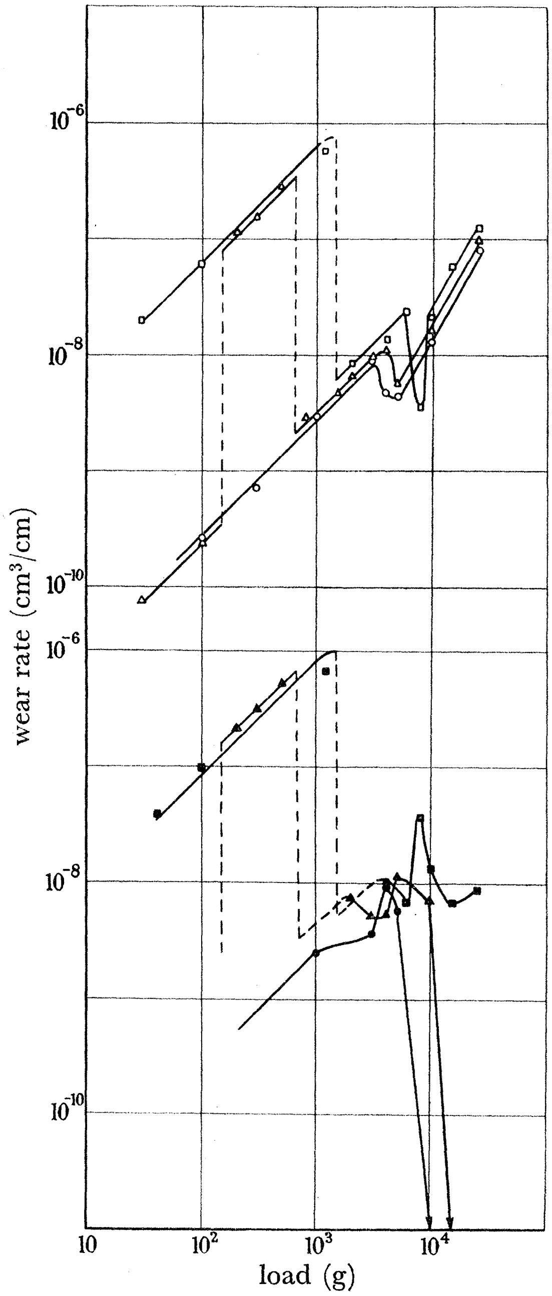

FIGURE 13. Effect of annealing the 0·78 % C steel. Sliding speed 100 cm/s. ○ (pin), ● (ring), hot-rolled, 278 V.p.n.; △ (pin), ▲ (ring), annealed, 258 V.p.n.; □ (pin), ■ (ring), annealed, 198 V.p.n.

(e) *Effect of other alloying elements*

In figure 15 graphs of wear rate against load for three alloy steels are compared with that of a plain steel of similar carbon content (0·34 %).

The presence of 1·1 % chromium has not affected the transition loads appreciably. With 3·5 % Ni, T_1 has been displaced to some load less than 20 g and T_2 has also been lowered (from 7 to 8 Kg to between 4 and 5 Kg). The most striking difference is, however, associated with the 3 % Cr-Mo steel; while T_1 is unaffected, T_2 has been elevated to

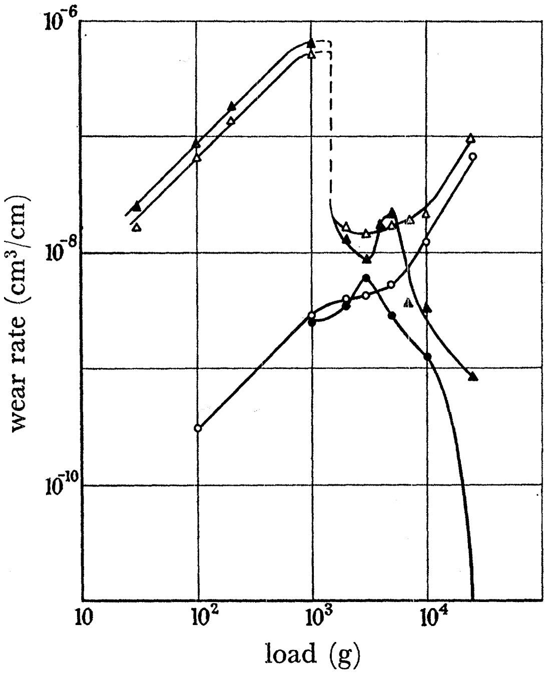

FIGURE 14. Effect of annealing the 0·98 % C steel. Sliding speed 100 cm/s. △ (pin), ▲ (ring), annealed, 216 V.p.n.; ○ (pin), ● (ring), hot-rolled, 319 V.p.n.

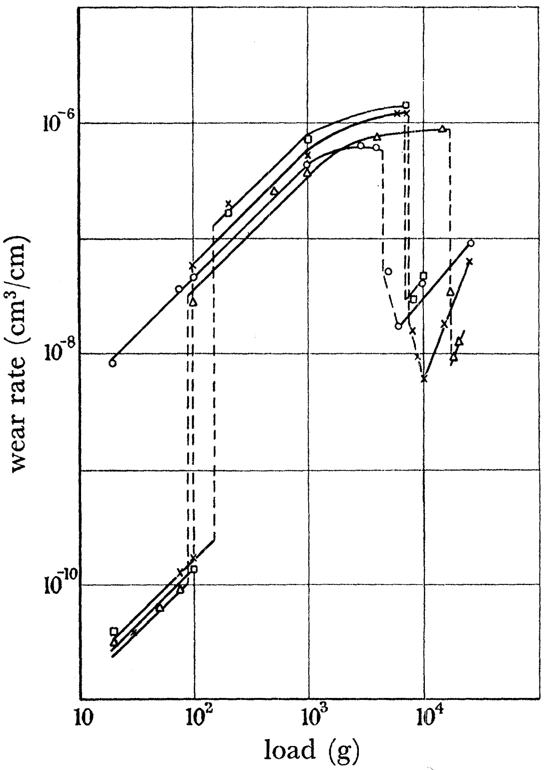

FIGURE 15. Wear rate plotted against load for three alloy steels compared with a plain steel of similar carbon content. Sliding speed 100 cm/s.

×	0·34 % C	—		205 V.p.n.
○	0·33 % C	3·5 % Ni		262 V.p.n.
△	0·33 % C	3·2 % Cr	0·42 % Mo	262 V.p.n.
□	0·315 % C	1·09 % Cr		174 V.p.n.

between 15 and 17 Kg. The range of severe wear is thus double that of the equivalent plain carbon steel.

In these experiments differences in the hardness of the steels were ignored. While all the hardness values lay appreciably below the critical value for the plain carbon steel (343 to 433 V.p.n.) the relative positions of the transition loads may have been affected to some degree. The hardest steels were the 3·5 % Ni and 3 % Cr-Mo (both 262 V.p.n.). It is interesting to note that a reduction in hardness of the 3·5 % Ni steel should tend to move T_2 closer to the value for the plain carbon steel and the apparent effect of the nickel content may be, in part, illusory. On the other hand, softening of the 3 % Cr-Mo steel should expand the already exceptional severe wear range of this steel.

It is clear that the effects of alloying need to be explored more systematically but these limited experiments reveal that the general pattern is not altered by moderate additions of common alloying elements.

(*f*) *Detailed wear rate–load curves*

In presenting the broad pattern of behaviour, attention has been focused on the transitions T_1 and T_2 which involve very large changes in the wear rate. Note has, however, been made of an inflexion in the wear rate–load curves for the 0·63, 0·78 and 0·98 % C steels (see figure 7). This inflexion, though representing a comparatively minor change in wear rate, is too prominent a feature of the curves to be ignored. A further aspect of the pattern that must be reviewed is the wear rate of the ring. While the assumption that the wear rate of the pin represents the combined behaviour is justified at light or moderate loads, the wear rates of the two components diverge in a marked and significant manner in the range above T_2 (see figure 4).

Both features are sharply defined in the curves for the 0·78 % C steel in figure 13. At loads greater than T_2 the pin curve appears to continue at first in a line which is an extension of the mild wear range below T_1. However, at some load (which increases as the hardness of the steel diminishes) the curve falls to a minimum and then rises with a steeper slope: the wear rate is no longer proportional to load. Over the same range the ring wear follows an entirely different course. At a point which coincides, at least approximately, with the minimum on the pin curve, the ring wear rate rises to a peak and finally diminishes rapidly. At the highest loads the ring usually showed a slight, fluctuating gain in weight and a meaningful wear rate could not be determined.

The same trend in the ring wear rate, i.e. a rise to a peak followed by a fall to low values, is apparent in the curves for the as-rolled and annealed 0·98 % C steel in figure 14, though in neither instance does the pin wear rate show a definite minimum. The peak in the ring wear rate curve seems in fact to be the most constant feature of this transition, which will be referred to as T_3.

In these examples T_2 and T_3 were separated by a considerable interval of load and a similar interval was observed in the curves for the 0·63 % C steel (the pin curve is shown in figure 7). Reference may, however, again be made to the curves for the 0·52 % C steel in figure 4. It is now possible to interpret the shape of the pin and ring curves as signifying that T_2 and T_3 lie close together. The same interpretation can be applied to the shape of the pin wear rate curves for lower carbon steels at loads slightly above the

T_2 transition (see figures 7, 15) and reference may be made to figure 16 which illustrates the trend of the T_2 and T_3 loads as the carbon content varies. Because of the complication introduced by differential hardness, only results for steels of fairly uniform hardness have been plotted (annealed steels in the case of high carbon contents). While the results lack precision, the graph reinforces the conclusion that at low carbon contents T_2 and T_3 tend to merge together, effectively obscuring the latter transition. It will, of course, be appreciated that unless measurements are made at narrow load intervals it is impossible to define the shape of the wear rate–load curves in the region of T_3 with much precision.

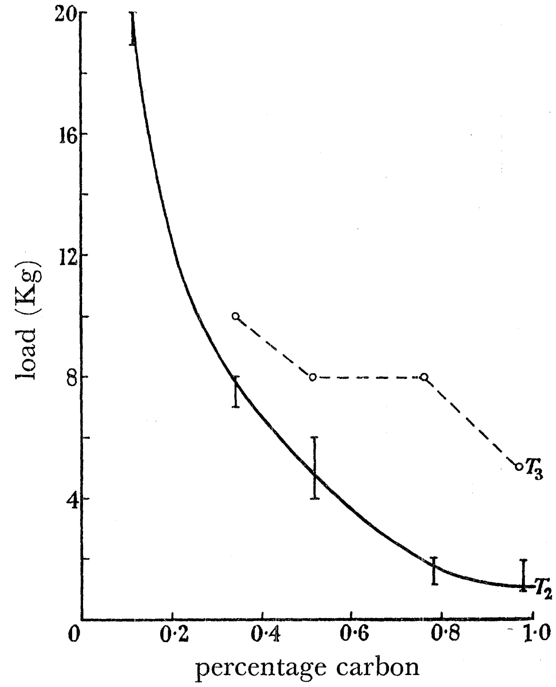

FIGURE 16. Variation of the T_2 and T_3 transitions with carbon content for steels of roughly constant hardness. Sliding speed 100 cm/s. % C: 0·12, 0·34, 0·52, 0·78, 0·98; V.p.n.: 141, 205, 212, 197, 216.

As the existence of this transition was not suspected until a comparatively late stage of the work, the experimental points in many of the graphs used to illustrate the T_1 and T_2 transitions are too sparsely distributed to identify the detailed shape of the curves. The lines have, therefore, been drawn simply to fit the points available and this must be borne in mind in any critical appraisal of the graphs.

It must be noted that the change in pin wear rate in the T_3 region resembles, in magnitude and form, the transition observed by Mailänder & Dies (1943) when soft iron pins were rubbed on hard steel disks (see figure 2) and by Kauzlarich *et al.* (1961) with hard steel pins on hard steel rings. Unfortunately, these authors did not report the wear rate of the rotating components and it cannot be certain that the comparison is valid. Nevertheless, the similarity should be recalled in part II when the meaning of the T_3 transition is considered; it will be demonstrated that this transition still takes place with soft pin/hard ring combinations.

4. Discussion

When this work began the existence of only one transition was suspected, that from severe wear to mild, but it is now evident that the basic pattern of behaviour, as manifest in the trend of the wear rate with load, embraces three transitions: (1) a change from mild to severe wear at relatively light loads (T_1), (2) a change from severe wear back to mild wear at higher loads (T_2), (3) a perturbation in the mild-wear rate at loads above T_2, with the wear rates of the pin and ring diverging (T_3).

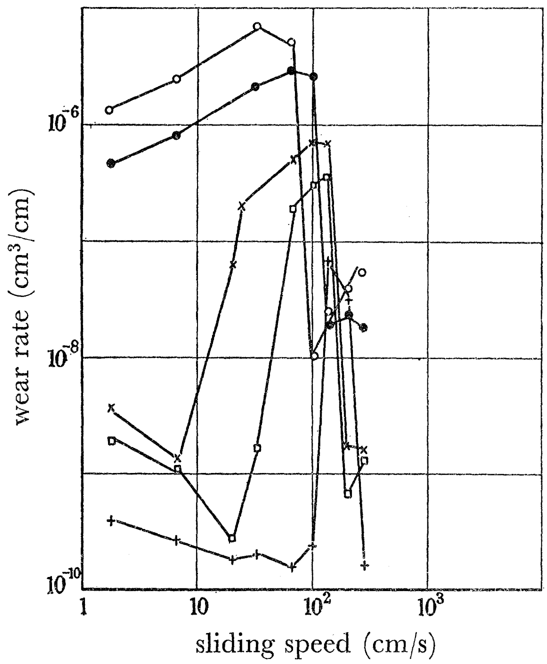

Figure 17. Change of wear rate with sliding speed for the 0·52 % C steel. Loads: +, 20 g; □, 500 g; ×, 1 Kg; ●, 5 Kg; ○, 10 Kg.

The complete pattern is, however, rarely observed. The transition loads vary widely with the sliding speed and with the composition and hardness of the steel; if these factors are selected arbitrarily one or more of the transitions may not appear within the range of load investigated and in the limit, the wear rate–load graph may be a continuous line representing either mild wear or severe wear at all loads. Without foreknowledge of the full pattern this diversity is perplexing and it is hazardous to compare the wear rates of various steels since, in slightly differing circumstances, these may be almost identical or differ by two orders of magnitude. In the last respect, it is remarkable how closely the wear rates do agree when equivalent states are compared. Thus referring to figures 7, 8, 10, 11 and 15 the spread of the mild wear rate below T_1 and of the severe wear rates between T_1 and T_2, is only a factor of 2 to 4. (The spread is greater above T_2 but comparison is then usually marred by the uncertain position of the T_3 point.)

An increase of sliding speed lowers all the transition loads and for fixed loads there must be critical values of speed at which equivalent changes in the wear rate occur. In figure 17 the wear rates shown in figure 5 are replotted as a function of speed and this produces a pattern which at high loads (e.g. 5 and 10 Kg) closely resembles the wear rate–speed curves described by other workers (Kehl & Siebel 1939; Kragelskii & Shvetsova 1955; Archard 1959) (cf. figure 1). However, these high-load curves show the existence of only one critical speed, equivalent to the T_2 transition; the low load curves reveal the existence of a second critical speed, equivalent to T_1. The analogue of T_3 cannot be identified in figure 17; measurements at many closely grouped speed intervals would be required to resolve this transition.

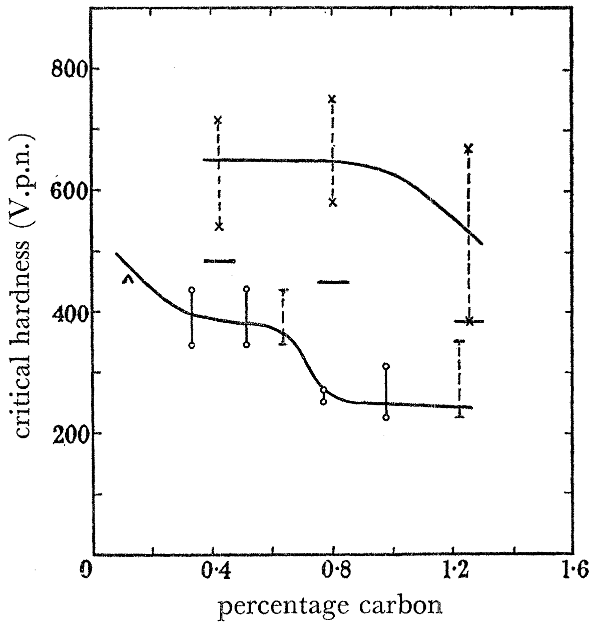

FIGURE 18. Change of critical hardness with carbon content. ⟂, Derived from results of Kehl & Siebel (1939). ⁑, Derived from tests in hydrogen by Rosenberg & Jordan (1934). (The horizontal bars indicate the minimum hardness values studied.) ⚲, Present tests.

An increase of hardness elevates T_1 and depresses T_2 and T_3 and at some critical hardness, which varies with the composition of the steel, T_1 and T_2 merge together, eliminating the range of severe wear. Critical hardness values have been determined for most of the steels and it is interesting to compare these values with analogous observations by other workers. With reference to figure 1, Kehl & Siebel (1939) in their study of the effects of sliding speed at fixed load, observed that samples of 0·64 % C steel, quenched and tempered to 445 V.p.n. or more gave mild wear at all speeds, while samples of 348 V.p.n. or less showed the characteristic transition from severe to mild wear. In similar tests with 1·23 % C steel the corresponding values were 350 and 230 V.p.n. These results dovetail neatly into the trend established in the present work as shown in figure 18. It is gratifying to find that results from different test equipment and procedures blend so well together and the critical hardness would seem to be a factor of basic importance. However, figure 18 also includes results derived from experiments by Rosenberg & Jordan (1934) with quenched and tempered disks rubbing, at fixed load and speed, in an atmosphere of hydrogen; it is evident that in these circumstances severe wear persisted to much higher hardness values. Moreover, these authors reported that disks rubbed in air gave mild wear at all hardness levels. These seemingly discordant observations can be harmonized with present findings if two assumptions are made. First, that the critical hardness varies with the nature of the atmosphere, and secondly, that the minimum disk hardness tested by Rosenberg and Jordan exceeded the critical hardness for air-rubbed steels. The first assumption will be vindicated in part II of this paper. The second is justified by figures given in Rosenberg & Jordan's own paper; the minimum hardnesses tested appear to be those indicated in figure 18 by short horizontal lines and it is evident that they exceed by a definite margin, the critical values for air-rubbing. Viewed in this light, the results are complementary rather than discordant.

The influence of hardness bears upon the issue of changes associated with the composition of the steel. For a given state of heat treatment, an increase in carbon content automatically involves an increase in hardness and the intrinsic effects of carbon content can only be ascertained by varying the heat treatment to give parity in hardness. While the results in figure 16, for steels of reasonably similar hardness, indicate that there is a genuine fall in the T_2 and T_3 values as the carbon content increases, the sharp upward trend of the T_1 load (figure 9) is undoubtedly a spurious effect associated with the varying hardness; the T_1 values for annealed high carbon steels were extremely low (see figures 13 and 14). The same ambiguity limits the information which can be derived from the comparative tests on alloy steels (figure 15) and it is clear that in any thorough appraisal of the influence of alloying elements it is essential to maintain, as closely as possible, constant hardness as well as constant carbon content. These considerations assume especial importance when it is appreciated that, in practice, high carbon steels and alloy steels are usually employed at hardness levels in the range where rapid changes in the wear pattern may be expected to occur.

Finally, reference must be made to certain differences observed in the results from the two pin and ring machines. In equivalent circumstances the wear rates corresponded closely and in general form the graphs of wear rate against load were identical, but the T_2 transition invariably occurred at somewhat lower loads on machine *B* than machine *A* (cf. figures 4 and 10). The lack of reproducibility of different test equipment is, of course, a problem which bedevils wear testing in general, and the fact that the results from machines of similar (though not identical) design should vary in this way emphasizes the importance attaching to the broad trends of behaviour. Once these trends have been established, it is usually possible to recognize the elements of pattern prevailing in any circumstances and to assess and compare the results accordingly. It is hoped that the present findings will help to provide the reference framework required when results from separate investigations are compared.

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