Substitute alloys as bearing materials

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MODERN engineering depends in many instances upon bearings, components which allow relative motion to occur between the members of a mechanism. Bearings may take many forms but the most widely used types are plain and rolling bearings. The continuous demand for better power-to-weight ratios for increased mechanical efficiency leads to a constant demand for bearing materials of improved strength to operate at increased speeds under heavier loads at higher temperatures. Whilst the materials of construction should be as cheap as possible, an important consideration in developing countries, particularly India, is the availability of the raw materials, thus the metallurgist must not only search for improved bearing materials but also for suitable substitute indigenous materials.

Plain bearings

In plain bearings the load is transmitted between moving parts by sliding contact and the criterion of satisfactory performance of the bearing is minimum wear of the components together with freedom from seizure and freedom from mechanical failure by deformation or fatigue. To carry a hard steel shaft, usually specified for its mechanical properties, a bearing material must be comparatively soft to avoid wear of the harder material yet strong enough to withstand heavy loads without distortion and without suffering fatigue. Soft bearing materials also allow abrasive particles to become embedded and thus reduce abrasive wear. As a low hardness is usually associated with a low melting point, high spots of soft bearings are easily removed by sliding contact without damage to the mating surface and without the risk of seizure. However, low hardness is usually associated with low fatigue strength and as stress levels are raised the demand is for harder bearing materials to improve the load carrying capacity but with the minimum loss of friction and wear properties.

White metal, probably the most widely used plain bearing material, is usually tin or lead based or one of their intermediate alloys. The most generally used tin base alloy contains 7–10% antimony and 3–5% copper, the principal constituents being SbSn, Cu_6Sn_5 and ternary peritectic complex (Fig. 1). Hardness and mechanical properties are only moderately affected by composition[1] and fatigue strength appears even less sensitive to composition.[2] At 100°C hardness is quoted as ranging from 11–16 HV[1] and the fatigue strength for 10^7 cycles from 1·05–1·25 tons/in.[2] Alloying elements added to increase hardness appear to have no effect on the bearing fatigue strength.[3]

Lead base alloys usually contain antimony, tin and copper in the form of intermetallic SbSn and Cu_6Sn_5 compounds. These alloys are cheaper than the tin base alloys of similar hardness but are slightly inferior substitutes regarding wear and fatigue properties. They may be alkaline hardened by the addition of sodium, calcium, lithium etc. Intermediate alloys of high lead and tin content are widely used but they appear to have no advantages over the other white metals. The success of white metals is generally regarded as being due to the correct compromise between softness to avoid wear, and strength to resist fatigue.

Copper base alloys, stronger bearing materials than the white metals at operating temperatures, range from the phosphor bronzes (10% Sn 0·5% P) through the leaded bronzes (e.g. 80 : 10 : 10 and 76 : 4 : 20, Cu, Sn, Pb) to the copper lead alloys of up to 50% Pb, (Fig. 2). The wear properties of a leaded bronze have been shown to be better than those of white metal.[4] The hardness of copper lead alloys is quoted to vary according to composition from 20–70 HV.[3] Journal wear increases with increase in hardness[6] but the fatigue strength increases roughly in the same proportion as journal wear.[6] Increased journal hardness can help to minimise wear. A disadvantage of copper lead alloys is their susceptibility to lubricant corrosion of the lead phase.

A substitute bearing which offers a compromise between alloys soft enough to avoid wear, alloys hard enough to resist fatigue and alloys able to resist corrosion, has been evolved by the use of coated or overlay bearings in which a strong metal such as a copper base metal has a soft metal overlay. Further economy can be effected by using copper lead alloy as an interlay between a steel base and the overlay (Fig. 3). The manufacture of these bearings requires highly specialised processes to provide the overlay usually thinner than 0·002 inch to avoid fatigue failure with the loads usually applied to copper lead alloys. The overlay plated copper lead bearing is one of the most widely used high duty engine bearings, but as bearing duties become more arduous

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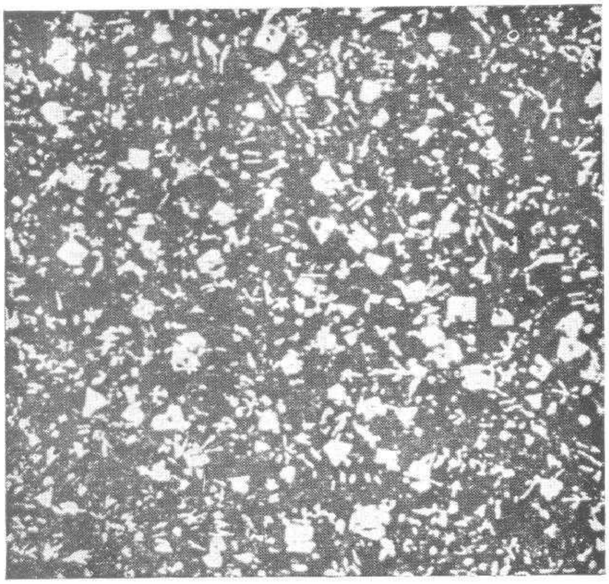
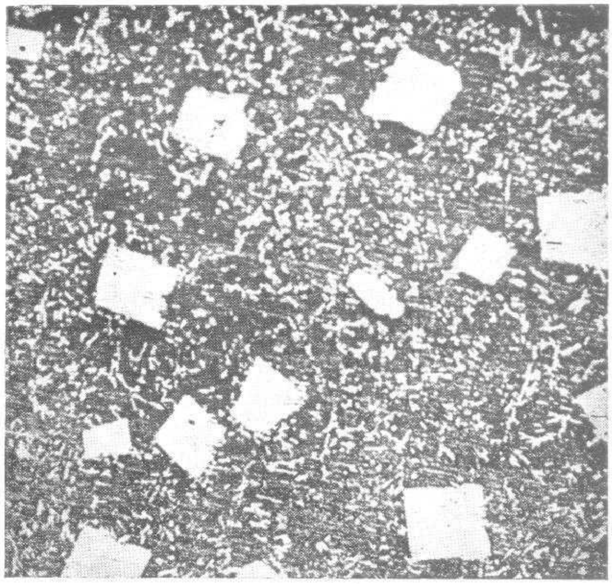
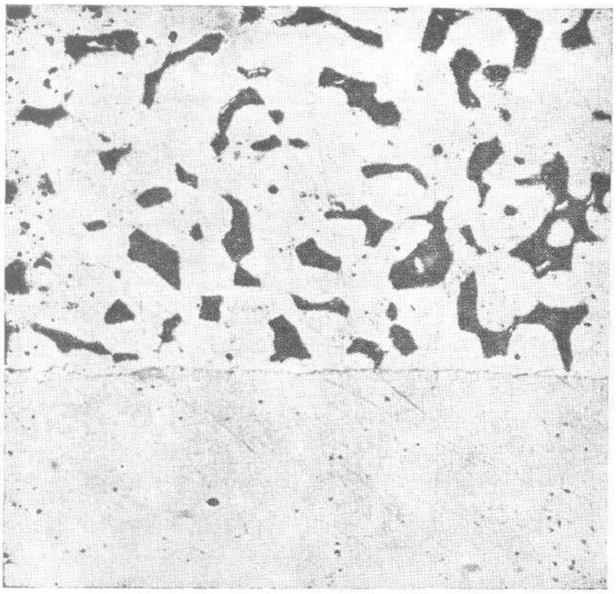


(a) Gravity cast



(b) Centrifugally cast

1 *Structure of tin-base white metal containing antimony and copper; Etched nital* ×100



2 *Copper-lead (70-30) on steel shell; unetched*

the continuous search is for something better in readily available material.

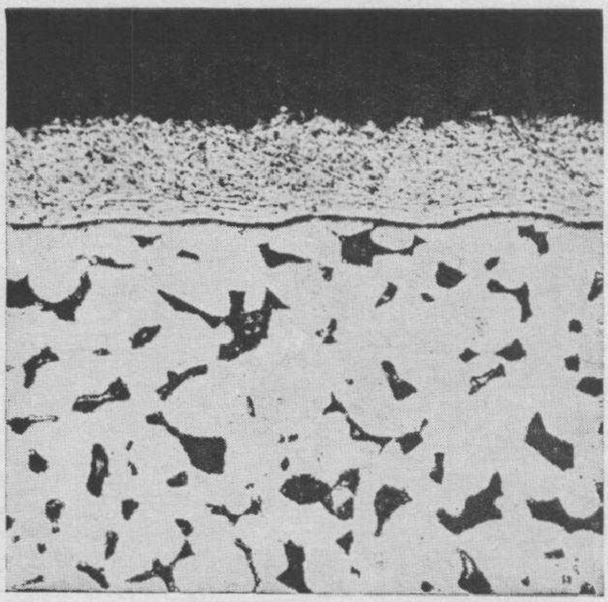
As aluminium, a comparatively cheap material in abundant supply, will form alloys with useful properties, this field has been explored in the search for substitute bearing materials. The conventional approach of using hard metal compounds in the aluminium matrix, to produce a structure analogous to that of white metal, has met with some success. The main types are alloys with up to 15% Cu, alloys containing small amounts of Pb, Sb, Cu, Mn and Fe, alloys with Cd, and alloys with Cd and Si. A different approach of using another soft metal, namely tin, has produced good results since suitable methods of bonding the aluminium alloy to a steel backing have been developed.[7] If the tin takes the form of a coating around the aluminium grains the strength of the material is limited by the low melting point of the tin. By suitable cold working, followed by heat-treatment and recrystallisation, the distribution of tin can be confined to the edges of the aluminium to produce a structure in which both the tin and aluminium phases are continuous. Such alloys having a reticular or net-like structure (Fig. 4) have been found to have adequate bearing properties. The addition of a small amount of hardener such as Cu is beneficial and seems to offer the best combination of strength (some 2–4½ times the load carrying capacity of white metals[8]), wear and corrosion resistant properties at present available.

Further work on the development of suitable overlays for aluminium bearings to aid running-in and minimise wear of nitrided and hardened journals will probably result in the increasing use of the bearings in high duty automotive applications.

Rolling bearings

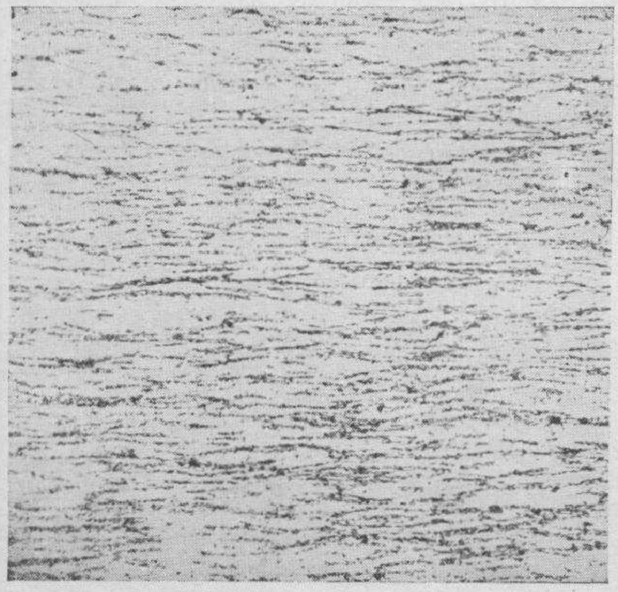
In the case of plain bearings, conformal contacts, one component is generally made of soft material to enable conformity to be maximised. With rolling bearings, counterformal assemblies, the concentration of stress necessitates material of great hardness leading to a different type of failure. Although ball and roller bearings are basically rolling elements, in operating mechanisms they are also subjected to some wear by sliding and to chemical attack by lubricants and environment. Their useful life is usually limited by surface disintegration, pits being formed by a fatigue process. The engineering requirements of ball bearing steel are dimensional stability, high resistance to wear, high elastic limit to avoid plastic deformation under load, and high fatigue resistance to contend with high alternating stress. For economic reasons cost must be low. A high carbon steel normally satisfies the requirements if a carbide forming metal is incorporated to increase hardness, give hardnenability and allow oil quenching to minimise distortion during heat-treatment. For conventional ball bearings, En 31, 1·0% C, Cr steel is used.

Engineering progress imposes severe requirements on rolling mechanisms and in some specific application such as aero-engines, atomic power and space exploration ; due to extreme operating temperatures and environments conventional En 31 steels are not suitable and superior materials are required. The ultimate assessment of a bearing material is its performance in practice but, as full scale testing is a long and expensive process, an accelerated laboratory test has been developed to screen potentially-suitable materials, to assess in turn, the effect of material variables and to study the mechanism of failure.

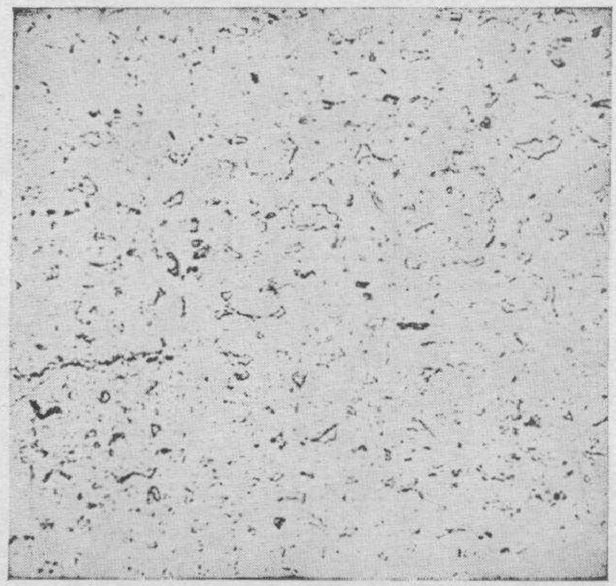


3 *Lead-tin (90-10) overlay on copper-lead (70-20) interlayer, unetched* ×250

The NEL rolling four-ball test[9–11] simulates in simple



(a) Cold worked

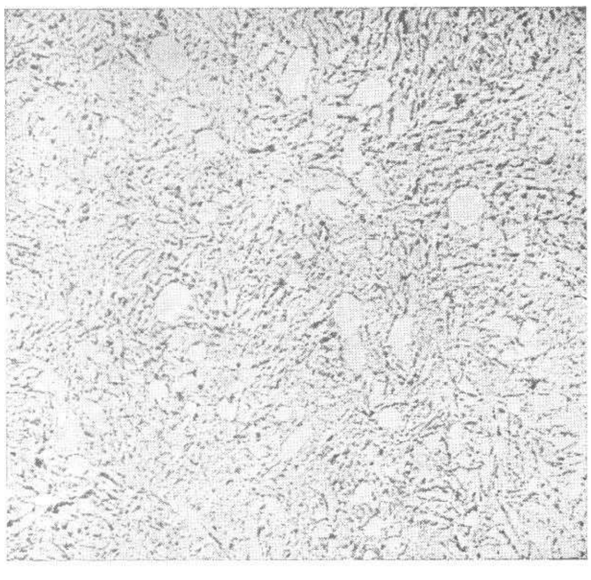


(b) Cold worked and annealed (reticular)

4 *Structure of aluminium-tin (80-30) bearing alloy* ×250

5 *Transverse cracks in bearing surface ; Electron micrograph o, C replica* ×19 000

from the rolling and sliding experienced in angular contact ball bearings, produces the same type of failure as that obtained in practice and, in many instances, correlates well with the results of full scale test and practice.[9,10,12,13] To test materials not available in ball form, the upper test ball may be replaced by a ball ended specimen.[14] A temperature-controlled induction heater incorporated in the lower race enables tests to be carried out at elevated temperatures.[15]



6 *Structure of En 31 ball bearing steel ; Etched nital ; Electron micrograph of C replica* ×3 000

With En 31 ball bearing steel, under the conditions of test, there is an optimum hardness range for rolling contact fatigue life ; thus microstructure and heat-treatment are important.[16] Surface finish, the method of finishing and the stress induced can greatly influence the performance.[16] Fibre orientation has an effect, the worst condition appearing to be when the angle of fibre orientation in relation to the bearing surface coincides with the maximum shear plane.[15] The steelmaking process can influence results ; vacuum techniques appear to be beneficial.[17] There appears to be a trend towards increased rolling contact fatigue life with improved fatigue strength.[17]

Substitute materials potentially suitable for elevated temperature use have been compared with En 31 steel at ambient and elevated temperatures with various lubricants.[18,19,20] Under all conditions of liquid lubrication, high speed tool steels (18-4-1 W. Cr. V type) were superior to the other steels tested, particularly at elevated temperature. They were less prone to deleterious lubricant effects. Hardened 12% Cr type stainless steel, although inferior to En 31 steel at ambient temperature, was superior at elevated temperature and also more resistant to deleterious lubricant effects.[18,20]

In the search for cheaper substitute high speed tool steels similar results to those with 18-4-1 type were found with substitute high speed tool steel containing molybdenum, M. 2 (6.6.4.2 Mo. W. Cr. V) type and with other substitute molybdenum high speed tool steels of lower alloy content, M. 10 (8.4.2 Mo. Cr. V) and M.50 (4.4.1 Mo. Cr. V) types. Heat treatment of these materials is very important to give a satisfactory carbide structure of optimum hardness. Retained austenite is deleterious.[19] Vacuum melted material has been found to be susceptible to overheating and grain growth at temperatures normally used for air melted material.[20] The steelmaking procedure also has an important bearing on the incidence of failure ; acid material appears to be superior to basic electric material and vacuum methods are beneficial. The choice of material combination has been shown to be a major factor in enhancing or reducing the performance of either mating material.[21] The hardness of both mating surfaces is important to ensure rolling contact fatigue life.[21]

As conventional liquid lubricants are unsuitable at elevated temperatures and are lost by evaporation in low pressure environments, some rolling bearings must either operate unlubricated or be lubricated by solid film or by surface treatments. Failure under unlubricated conditions is not by the usual fatigue mechanism but by wear, loss of surface material terminating the useful life due to excessive wear, noise and vibration. Under unlubricated test conditions at ambient temperature tungsten carbide balls gave the best performance. Tungsten carbide was the only material comparatively unaffected by elevated temperature.[18] Wear of tungsten carbide appeared to increase with increase of carbide size and increase of the amount of matrix material.[20] Use of a solid lubricant, MoS_2, was beneficial ; wear, as assessed by loss of weight, was eliminated in tungsten carbide, stellite and high speed tool steels and reduced with other materials.[18]

By suitable surface treatment, substitute materials can, in many instances, replace conventional materials. Owing to through hardening and heat treatment difficulties with conventional En 31 ball bearing steels, case hardened En 34 steels (low Ni, Mo) has been found to be satisfactory for large races of ball and roller bearings. Carburised En 34 steel specimens have been subjected to rolling four-ball test.

Summarised typical results are given in Table I.

TABLE I Mean life tests on En 31 and carburised En 34 steel specimens: total axial load 600 kg. mineral oil lubricated

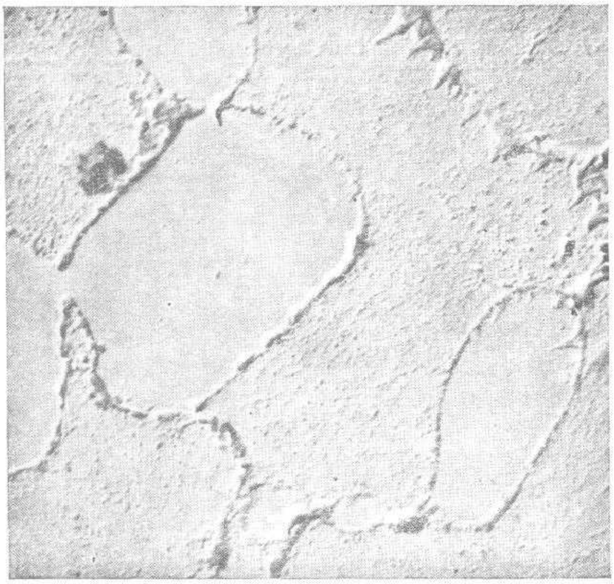
Specimens	Mean life (min)	No. of (tests)
En 34 steel, air melted, carburised	96	10
En 34 steel, vac. treated, carburised	191	10
En 31 typical basic electric	94	14
En 31 typical neutral O. H.	122	16
En 31 typical acid O. H./Vac. remelted	168	20

The test results show carburised En 34 steel specimens to be comparable with the through-hardened En 31 steel specimens manfactured by the same process. Vacuum techniques appear to be benificial to both types of steel; soft nitriding and a duplex nitriding treatment were of no avail in rolling contact, the nitrided surfaces suffering premature cracking and pitting failure.[20] Under conditions of unlubricated contact, however, nitrided En 40 steel showed wear resistance comparable to much more expensive high speed tool steels and stellite. Soft nitriding in an oxidising bath produces an oxide-rich, nitrided surface layer with good frictional properties and was beneficial in reducing the wear of M. 50 high speed tool steel in unlubricated rolling contact.[20]

Under conditions of high stress rolling contact changes occur in conventional En 31 ball bearing and high speed tool steels. The changes manifest themselves by increased hardness, plastic deformation and metallographic change at surface material.[16, 22] Cracks leading to failure appear to initiate in the severely stressed material (Fig. 5). Crack propagation appears to be controlled by the envirnonment and the nature of the lubricant. Water in the lubricant can cause accelerated failure,[23, 25] and hydrogen embrittlement,[26] as in water cooled rolling mills,[27, 28] can be a contributory factor. Hardened and tempered En 31 steel (Fig. 6), consists of carbides in martensite whereas the deformed metallographically changed material shows an absence of carbide spheroids (Fig. 7). The increased hardness may be due to solution of the carbides as a result of high contact stresses, local high temperature flashes and rapid quenching under pressure by bulk material and lubricant. Absorption of gases from lubricant breakdown may contribute to hardening. Below the surface, carbide-free zone, stringer type carbides are found (Fig. 8). These may be formed by annihilation

7 *Transverse section through bearing track showing deformed metallographically changed surface material ; Electron micrograph of C replica ; Ni plated to protect edge during preparation* ×35 000

8 *Stronger type carbides in sub-surface area of bearing track ; Electron micrograph of C replica* ×22 000

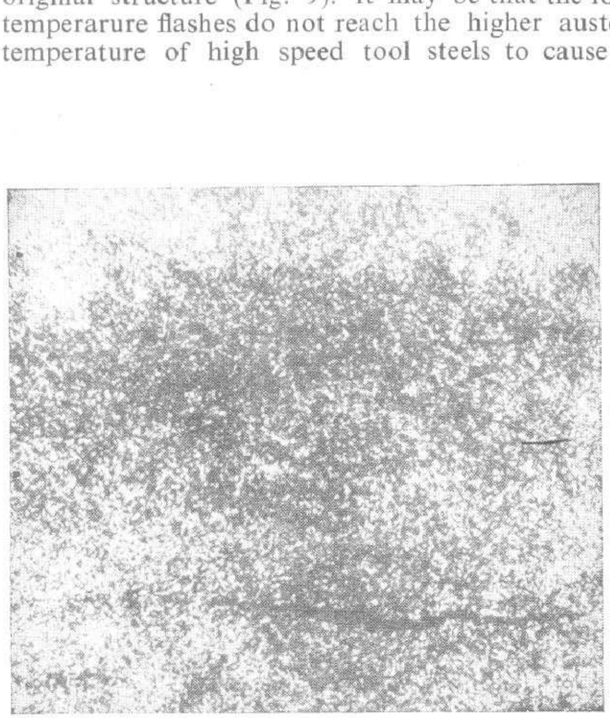


(a) Original structure

(b) Worked surface material

9 *Structure of 18-4-1 high speed tool steel ; Electron micrographs of C replicas* ×10 000

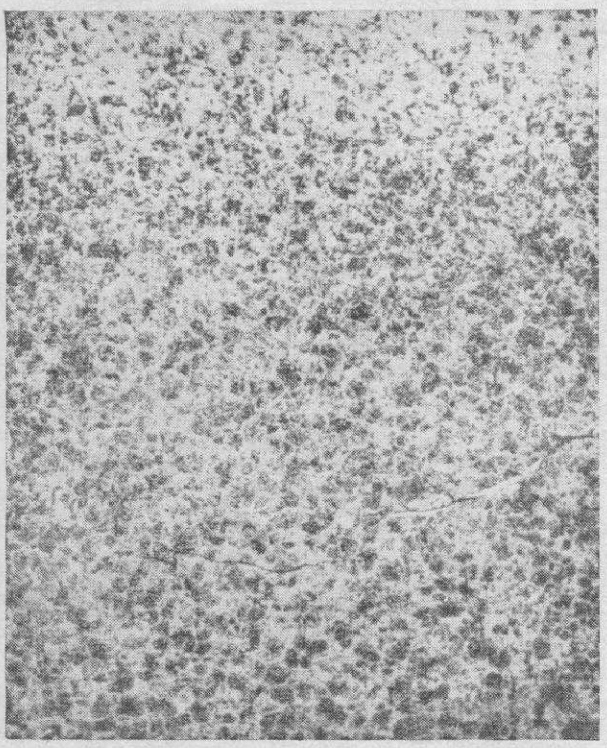
of the coarse carbides by plastic deformation causing extrusion and intrusion. The worked surfaces of high speed tool steel rolling elements still retain carbides although these are smaller than the carbides on the original structure (Fig. 9). It may be that the local high temperarure flashes do not reach the higher austenitizing temperature of high speed tool steels to cause carbide solution. Cracks probably do not initiate so readily in the carbide containing tougher structure of stressed high speed tool steel and this may explain the improved performance particularly resistance to deleterious lubricant effects or environments.



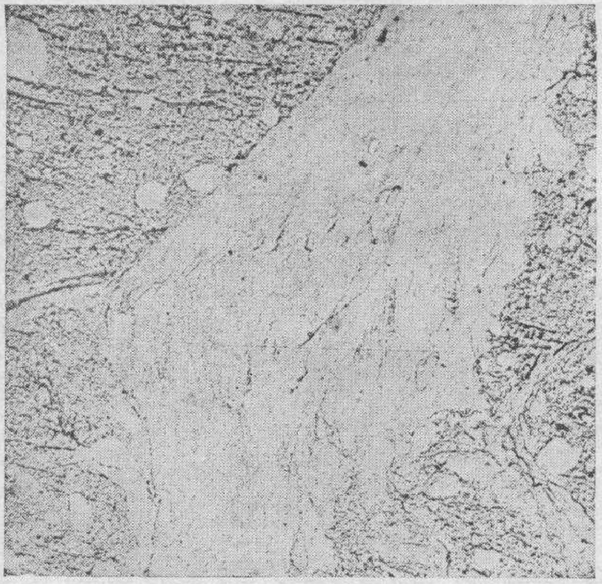
10 *Transverse section through bearing track showing sub-surface metallographic change and crack ; Etched Nital ; Specimen Ni plated to protect edge during preparation* ×600

Other changes occur in En 31 steels in the sub-surface area of contact in the region of calculated maximum Hertzian stress. Transverse sections through bearing tracks show the presence of localised areas of tempered martensite or mechanical troostite, softer than the original material. This may be a tempering phenomenon, heat being generated by elastic hysterisis due to cyclic stressing or a strain induced transformation. Sub-surface cracks are found in these areas. It may be that the tempered material is incapable of supporting, without plastic deformation, the stresses imposed and cracks initiate which propagate parallel to the surface (Fig. 10).

Longitudinal sections through bearing tracks show, in specific sub-surface regions, similar metallographic change and sub-surface cracks but elongated white etching areas appeared to be associated with the cracks (Figs. 11 and 12). Most of the white etching areas appear to have a smooth appearance, some show evidence of fine structural features and some markings suggestive of deformation (Fig. 13). Stringer-type carbides are associated with the edges of the white etching areas and in the finer structure (Fig. 14). Micro-cracks may initiate at stress raiser such as inclusions and local areas of untempered martensite may be produced by intensive heating brought about by local dislocations in the vicinity of micro-cracks. Heating of relatively short duration may be sufficiently intensive to exceed the austenitizing temperature, cause carbide solution, then rapid quenching by bulk material would give the hard martensite of measured hardness up



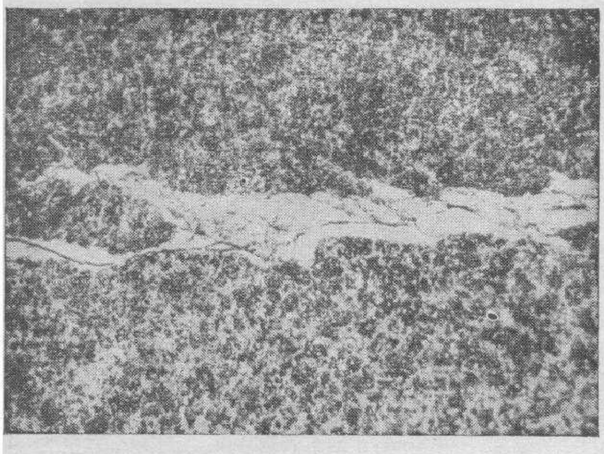
11 *Longitudinal section through bearing track showing sub-surface metallographic change, cracks and associated elongated white etching areas; Etched nital* ×350



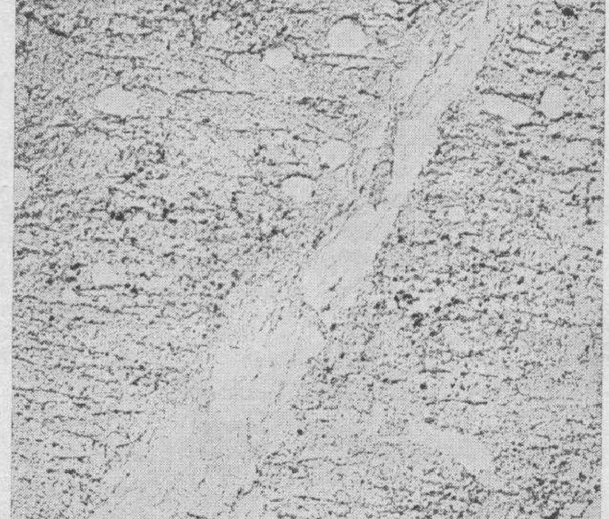
13 *White etching area in sub-surface region of rolling contact; Etched nital; Electron micrograph of C replica* ×2 900

to 1100 HV. Extreme hardness could also be due to high localised stress concentrations and this highly stressed material may not readily etch. In situ transformation of retained austenite could give rise to stress concentration due to a volume increase and thus initiate cracks. Rolling action produces similar elongated white etching material associated with cracks in specific sub-surface areas of high speed tool steel rolling elements.

Although some controversy exists as to whether cracks initiating rolling contact fatigue start at the surface and spread into the material, or start below the surface and spread outwards, investigation has revealed that both



12 *Cracks and associated elongated, white etching area in metallographically changed sub-surface material; Etched nital* ×620



14 *Metallographically changed material at edges of white etching area; Etched nital; Electron micrograph of C replica* ×2 900

mechanisms are operative, the more dominant depending upon prevailing circumstances. The propagation of surface cracks which begin at the edges of the contact pressure zone seems to be controlled by the nature of the lubricant and the environment. Sub-surface cracks start at depths associated with the region of maximum Hertzian shearing stress. The initiation of these cracks is facilitated by the presence of non-deforming, non-metallic inclusions breaking the metallic continuity within the stressed area. Transformation of retained austenite and hydrogen crack initiation and failure.

Conclusions

In the field of plain bearings the use of hardening techniques to improve white metals has been fully exploited and it appears that conventional alloying techniques have little else to offer. Higher strength alloys such as copper-lead have corrosion problems but are extensively used as interlayers for soft metal overlays and steel shells. As a substitute bearing material, aluminium alloys offer the best combination of strength, wear and corrosion resistance. Successful techniques of bonding to steel have rapidly increased the potential of aluminium in automotive bearing applications. Research on the use of hardening additions and suitable soft overlays should increase their use.

To improve the fatigue life and reduce the incidence of premature failure of rolling bearings the material should be as free as possible from deleterious, brittle type non-metallic inclusions. The substitution of vacuum treated for air melted steel improves performance. For specific applications substitute high speed tool steels of lower alloy content are satisfactory but it is essential to control the heat-treatment carefully to ensure optimum hardness, satisfactory carbide distribution, and minimum retained austenite content. Surface treatments can improve the performance of substitute materials in specific applications. Lubricating surface films, formed in situ on treated surfaces by special environments, may be a way of enabling simple materials to be used as substitutes for complex, highly alloyed materials.

Acknowledgements

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