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Introduction

The Vickers hardness of 100Cr6H steel located immediately below the surface of the raceway of a defective, lubricated Si₃N₄ hybrid spindle bearing was measured to be 900 HV MPa – a value significantly above the normal HV value of 720 HV. The bearing with a diameter of 50 mm and a running speed of 24,000 rpm was used in fully automated high-speed cutting operations. Taken in conjunction with the hardness depth profile, the unusual hardening observed suggests that the damage was caused by the dissipation of a large surge of frictional energy lasting several milliseconds. Instead of the surface pitting or split raceway that are typical of overloading, the 'materials' in the raceway seemed to have been 'plated' or 'rolled' onto the surface. The hardened area had a very fine microstructure with grain sizes about one tenth of those in neighbouring unhardened zones and could only be etched with great difficulty.

Experimental procedures and results

A segment was removed from the inner ring of the bearing for material analysis (see fig. 1). Prior to commencing metallographic analysis, a secondary electron image of the inner ring raceway was recorded and an element distribution map made of the area in which the 'plated' deposits were visible (see fig. 2). The sample was then nickel-plated and embedded in epoxy resin to achieve better edge sharpness. The various stages of specimen preparation are listed in table 1.

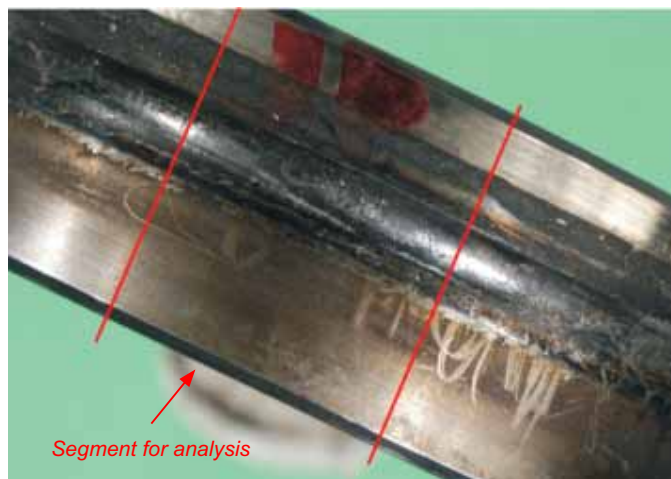


Fig. 1:
Location of segment removed for analysis

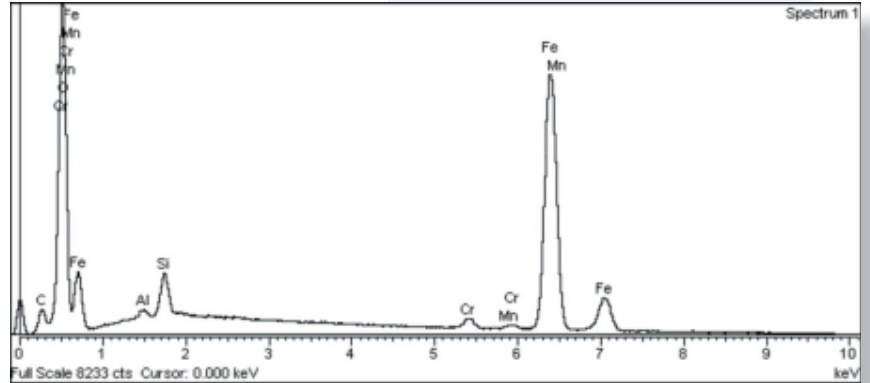
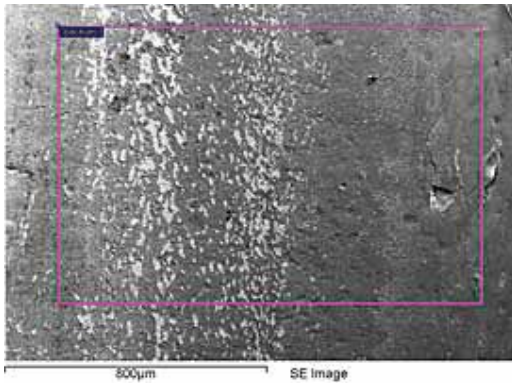
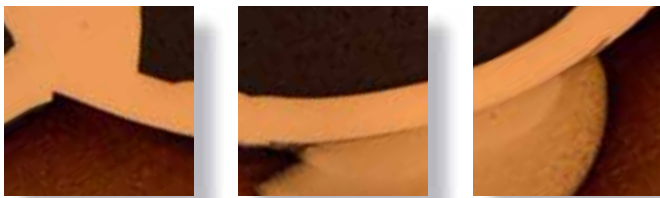


Fig. 2: Secondary electron image and element distribution map of the raceway of the bearing inner ring

After final polishing, the specimen was etched with Nital (fig. 3). After five seconds, the damaged area was only weakly etched and etching had to be repeated. After renewed etching, the other part of the specimen was overetched.

The microstructure of the bearing inner ring comprises finely acicular martensite with carbides that are in part linearly arrayed (fig. 4). The Vickers hardness number was measured to be 740 HV 0.2.

	Step 1 Grinding	Step 2 Grinding	Step 3 Grinding	Step 1 Polishing	Step 2 Polishing
Surface	MD-Piano	MD-Piano	MD-Allegro	MD-Dac	MD-Chem
Abrasive	Diamond	Diamond	Diamond	Diamond	Suspension
Grit / Grain size	120	220	9 μm	3 μm	0.04 μm
Lubricant	Water	Water	Green	Green	Water
Speed [rpm]	300	300	150	150	150
Force [N]	20	20	20	25	15
Time [min]	until plane	2	5	3	1

Table 1: Steps in the metallographic preparation of the specimen



Fig. 4: Microstructure of the undamaged region comprising fine acicular martensite with carbides. (Vickers hardness: 740 HV; etchant: Nital)

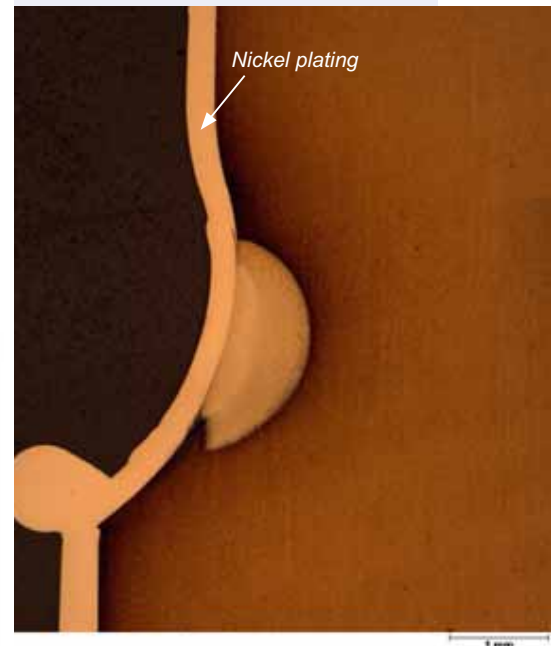


Fig. 3: Cross-section of the bearing's inner ring: low-magnification optical microscopy image of the damaged region (etchant: Nital)

The lower damaged part of the raceway with its strongly deformed microstructure and the plated deposits from an aluminium alloy can be seen in figure 5.

An etchant was sought that would etch the damaged and the undamaged microstructure uniformly. The best results were achieved using iron(III)-chloride as etchant (see figs. 6 and 7), which produced a uniform degree of etching over the entire specimen.

Hardness measurements were conducted on both the damaged and undamaged regions of the surface (fig. 8). The hardness-depth profile in the damaged area shows an initial fall in hardness to below 600 HV followed by an increase in hardness reaching almost 900 HV at a depth of 0.5 mm. Below 0.5 mm, the hardness decreases to below 500 HV (0.9 mm) and then rises again slowly eventually attaining the hardness values of the undamaged region at a depth of 2.7 mm. In contrast, the depth-hardness profile of the undamaged region showed a uniform hardness of 747 ± 12 HV 0.2.



Fig. 5: Image of the lower part of the damaged region (etchant: Nital)



Fig. 7: Detailed image of the damaged region (etchant: iron(III)-chloride)



Fig. 6: Low-magnification optical microscopy image of the damaged region (etchant: iron(III)-chloride)

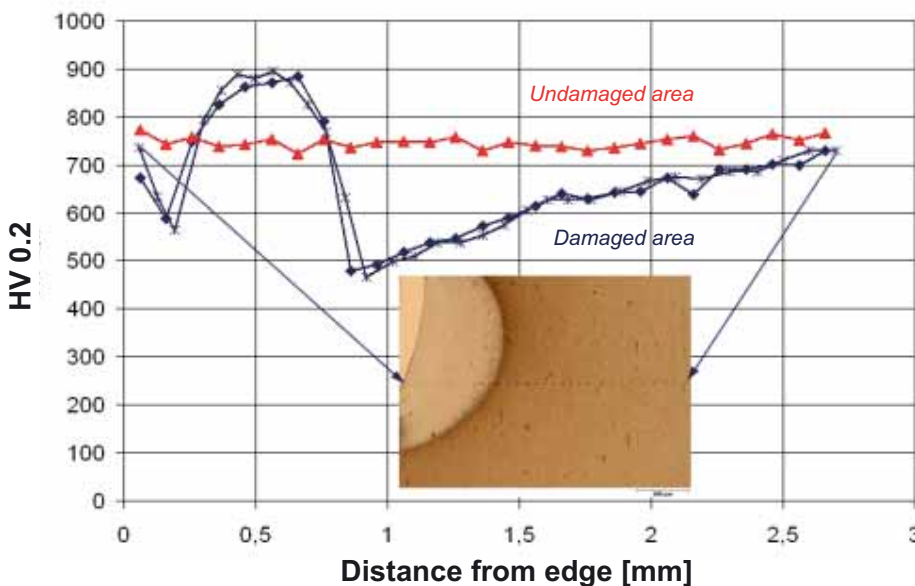


Fig. 8: Hardness profile of the undamaged and damaged regions

3. Conclusions

Poorly etchable white etching layers (WELs) arise from the severe plastic deformation that occurs during tribological stressing^{1,2}, especially when materials are subjected to high Hertzian stressing and unlubricated friction. WELs have a characteristically^{1,2} high Vickers hardness of up to 1,200 HV and a nanocrystalline microstructure with crystallites with a diameter between 10 to 25 nm. The module of elasticity rises to 220 GPa and the hardness values measured by nanoindentation can increase to 14 GPa. However, grain growth during heat treatment results in the loss of this microstructural state, with hardness declining to 300 - 400 HV.

WELs can be described as 'supersaturated' (nanocrystalline) α -iron in which no carbides are present.

Nanocrystalline, metallic materials are in a state of thermodynamic disequilibrium. They are typically formed during rapid quenching, severe plastic deformation (SPD) or from the presence of crystallization inhibitors. The rise in hardness is the result of the transformation of the residual austenite to the martensite phase. In the present case of a 100Cr6-based material, nanoscale microstructures in the system Fe-C can be formed subsequently by severe plastic deformation or by short-lived, high amplitude thermal flux densities.

In the case analysed here, chippings of aluminium alloys had penetrated the bearing raceway and were 'plated' or 'rolled' onto the surface causing a significant increase in frictional energy dissipation within the bearing. The very sudden failure of the bearing could not have been prevented by the monitoring sensor system.

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