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Citation for published version (APA):

DOI:
10.1063/1.104067

Document status and date:
Published: 01/01/1990

Document Version:
Publisher’s PDF, also known as Version of Record (includes final page, issue and volume numbers)

Please check the document version of this publication:
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Friction reduction and zero wear for 52100 bearing steel by high-dose implantation of carbon

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(Received 29 March 1990; accepted for publication 27 July 1990)

Ion implantation of carbon in the AISI 52100 bearing steel yields a distinct reduction in friction and wear. This improvement is strongly dependent on the implanted fluence. The coefficient of friction decreases from 0.6 to 0.2 for doses $>1\times10^{18}$ cm$^{-2}$ (energy 100 keV) and a wear reduction to nearly “zero wear” was obtainable even under severe wear conditions. The counterpart (unimplanted AISI 52100 steel ball) shows a similar behavior, which demonstrates that the tribological system is totally changed. Mössbauer spectroscopy and x-ray diffraction revealed that hexagonal $\epsilon$-carbide is formed on implantation. On the other hand, Rutherford backscattering spectrometry shows that for high doses a large fraction of the implanted carbon is not contained in this carbide.

With nitrogen implantation, a distinct reduction in wear occurs especially for high chromium steel, but without any decrease of the coefficient of friction. On the other hand, the wear behavior of 52100 bearing steel (low alloyed steel) could not be influenced by implantation of nitrogen. Singer et al. reported a 60% reduction of the friction by Ti implantations at high temperature and in a CO atmosphere. Similar improvements are published by Follstaedt et al. They implanted Ti and C into AISI 304 stainless steel, using transmission electron spectroscopy (TEM) for microstructural analysis.

We investigated the tribological behavior of the 52100 bearing steel implanted with carbon. We have applied Mössbauer spectroscopy and Rutherford backscattering spectrometry (RBS) to characterize the implanted layer. The doses were varied from $4\times10^{17}$ cm$^{-2}$ to $30\times10^{17}$ cm$^{-2}$ at an energy of 100 keV. The tribological tests were carried out on an oscillating ball-on-disk tester under severe conditions. The frequency of the ball was 7 Hz at a track length of only 2 mm, and the applied load amounted to 2.1 N. The ball, 4.76 mm in diameter, was also made of the 52100 bearing steel.

The implantations were performed on a Varian 350D implanter and the ion current density was 17 $\mu$A/cm$^2$. The disks were mounted on a water-cooled sample holder, so the temperature on the surface never exceeded 100 °C.

The $^{57}$Fe Mössbauer spectra were obtained with a constant accelerator spectrometer measuring the conversion electrons with a 96% He-4% CH$_4$ gas detector at room temperature. The spectra were fitted with a computer simulation, including isomer shift, quadrupole splitting and magnetic hyperfine field. RBS with 2 MeV He$^+$ ions and scattering angle 170° was used to measure Fe and C concentration profiles. The carbon concentration profiles have been calculated from the Fe signal using the missing element option of the computer program SQUEAKIE.

The friction behavior of the steel, implanted with a dose...
FIG. 2. Wear behavior of the unimplanted and carbon-implanted AISI 52100 steel. Implantation energy 100 keV. For the 3 X 10^18 cm^-2 disk the lower horizontal axis is used. For the other fluences the upper axis is used.

4 X 10^17 cm^-2 shows only a slight effect (Fig. 1). A reduction of the friction coefficient by 0.1 occurs for a very short time (about 4 min). A more marked effect can be seen when the disk is implanted with a dose of 1 X 10^18 cm^-2 (Fig. 1). Further improvement is obvious for a dose of 2 X 10^18 cm^-2 (Fig. 1). At a dose of 3 X 10^18 cm^-2, the reduced friction is observed for more than 6 h (1.5 X 10^5 cycles).

The corresponding wear results are shown in Fig. 2. The best results are obtained for the highest dose of 3 X 10^18 cm^-2. Normal wear occurs only for the very first cycles up to a depth of 0.15 μm which corresponds to the projected range of the carbon ions measured by secondary-ion mass spectrometry (SIMS) analysis. When this depth is reached, a very low wear rate is obtained with nearly no measurable wear for about 6 h. The ball shows also no wear for this period of time, no facet is formed, only a slight material transfer from the disk to the ball can be seen as black particles.

Preliminary investigations with 50 keV, 1 X 10^18 cm^-2 implanted steel revealed that it is possible to get rid of the relatively high wear (normal wear) for the first cycles, due to the fact that the carbon distribution is closer to the surface.

In Fig. 3 the Fe and C concentration profiles resulting from analysis of the RBS spectra are shown for disks implanted with 1 X 10^18 and 2.8 X 10^18 C/cm^2 at an energy of 100 keV. Since the density of the implanted layer is not known, the depth scale is expressed in at/cm^2. The high carbon fraction at the surface is an artifact of the computer program. The total amount of carbon found was (1.1 + 0.1) X 10^18 and (2.5 + 0.1) X 10^18 C/cm^2, respectively.

In Fig. 4, the Mössbauer spectra of the unimplanted and implanted bearing steel AISI 51200 are shown. For the implanted disks two extra sextets with respect to the unimplanted disk are observed. These subspectra can be assigned to crystalline ε-carbide Fe_3-x C, with 0 < x < 1. Similar to ε-nitride two iron sites are possible, coordinated with two or three C atoms. For Fe_4 C all Fe atoms are surrounded by two C atoms, while for Fe_6 C all the atoms are surrounded by three C atoms. Assuming equal Mössbauer fractions for both sites, the relative intensity of them gives the composition of the carbide. With implantation dose, the relative carbon fraction increases, resulting in Fe_52_ C for 2 X 10^18 cm^-2. Assuming equal Mössbauer fractions for Fe (α and γ) and the ε-carbide, the relative amount of those phases in the layer observed with Mössbauer spectroscopy can be found from the intensity of the subspectra. The result is shown in Fig. 5.
The relative amount of \( \epsilon \)-carbide is increasing with implantation dose. Conversion electron Mössbauer spectroscopy (CEMS) probes a depth of \( 9 \times 10^{17} \) Fe at/cm\(^2\) for \( \alpha\)-Fe about 1000 Å. For the K-conversion electrons of iron in nearly 100% pure carbon the depth is \( 4.2 \times 10^{18} \) C at/cm\(^2\). This means that we probe a depth of \( 1 \times 10^{18} \) C/cm\(^2\) implant. For the \( 2.8 \times 10^{18} \) C/cm\(^2\) implant this depth is \( 2 \times 10^{18} \) at/cm\(^2\). Therefore, the thickness of the layer observed with CEMS increases with the implantation dose. In this layer CEMS, able to distinguish the various iron compounds formed upon implantation, shows the presence of a carbide of composition \( \text{Fe}_{2.2} \text{C} \). On the other hand, the results in Fig. 3 show an atomic carbon concentration far in excess of the 30% of this carbide. Therefore, it can be concluded that a large fraction of the implanted carbon is present as pure carbon and is not contained in a carbide. This conclusion is confirmed by preliminary results of Auger electron spectroscopy (AES). The wear reduction, which increases with the dose, is probably a result of the \( \epsilon \)-carbide phase along with the carbon layer being formed. Our conclusion of finding crystalline \( \epsilon \)-carbide in a steel with low chromium concentration is in agreement with the results of Follstaedt et al.\(^7\) Analysis of our samples by x-ray diffraction confirmed the presence of crystalline \( \epsilon \)-carbide.

After annealing the implanted steel disk (dose \( 2 \times 10^{18} \) cm\(^{-2}\) at 500 °C the \( \epsilon \)-carbide is transformed to the Hagg carbide \( \text{Fe}_2\text{C}_3 \) according to Mössbauer and x-ray diffraction results. This is accompanied by a drastic change of the tribological behavior. A high wear of the ball occurs and the wear of the disk (adjusted to the contact pressure) increased by a factor of 10. This suggests that the \( \epsilon \)-carbide phase which disappeared on annealing contributes to the impressive reduction in friction and wear. Further investigations by depth selective Mössbauer spectroscopy are in progress.

Part of this work has been funded by the EEC program Basic Research for Industrial Technology in Europe (BRITE) under contact No. 1357.