The effect of ion implantation on the lifetime of punches

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Abstract

The electronics industry demands stamped parts with high performance. Therefore, punching tools like cutting punches with very high precision have to be used. In the case reported, the punches are mounted in a modular system and have to be resharpened or replaced after a certain number of strokes.

To increase the lifetime of the punches made of Vasco Wear steel, implantations with carbon, nitrogen, boron and titanium, and co-implantation with titanium and carbon were performed at energies from 50 keV to 200 keV and 600 keV and 700 keV with different doses in the region of several times 10^{18} cm^{-2}, measured perpendicular to the ion beam. A maximum increase in lifetime of a factor of 3.6 was reached. The surface roughness had a large influence on the increase in lifetime and the improvement caused by specific ion species. The maximum improvement was obtained for the lowest surface roughness ($R_a = 0.04$ µm). Therefore, when performing the implants, punches with low surface roughness should be used. The most successful ion species were boron and nitrogen for the lowest surface roughness used ($R_a = 0.04$ µm), and after changing the polishing procedure ($R_a = 0.14$ µm) titanium and nitrogen at medium energies (100–200 keV). High energy implantation (700 keV) resulted in an increase of a factor of 2.1 at lower doses (5.6×10^{17} cm^{-2}), but is uneconomical owing to the low current density. In laboratory wear tests (ball on disk) no improvement by ion implantation could be found. These results prove that it is difficult to compare field tests and laboratory tests because of different testing conditions.

1. Introduction

Ion implantation has been shown to be very successful for the wear reduction of steel in laboratory tests [1–3]. This technique has also been successfully applied to industrial applications, for example precision tools and medical prostheses, and aerospace components such as precision bearings [4, 5].

In this paper, the results of field tests concerning one special application, the improvement of punch lifetime by ion implantation, will be described. An increase in punch lifetime does not only save tools but also reduces the machine down-time because of the longer intervals between replacement of the punches. The down time is often the most important cost factor.

2. Experimental technique

2.1. Experimental conditions

For all experiments, Vasco Wear, a steel with very good wear characteristics was used. In laboratory wear tests and field tests, this steel had the lowest wear rate compared with the other steels tested. The punches were designed for the unique "Stepper-Modular-System". All components of this system are completely interchangeable.

The punches used for the experiments were wire eroded and polished to a surface roughness of 0.04 µm (R_a value) or 0.14 µm respectively. The Stepper-Module-Die ran in a Bruderer high-precision press BSTA 25 to (250 kN) at 300 strokes min^{-1} and a feeding rate of 100 mm s^{-1}. The tests were carried out with lubrication (film thickness of oil, 0.2 mm) giving a maximum punch temperature of about 200 °C. The stamped material was stainless steel (AISI 301) with a thickness of 0.5 mm. For each test, a new die plate made of Vasco Wear was used so that we had the same conditions for each punch. With a new die plate, a burr height of 0.02 mm was obtained on the stamped part. The field test was stopped when the burr height had increased to 0.1 mm.

For laboratory wear investigations, a ball-on-disk tribometer with oscillating ball made of AISI 52100 steel or tungsten carbide was used. The oscillation frequencies were 2 Hz, 7 Hz, and 10 Hz and the load was 2.2 N. The track length was 2 mm. The samples were disks with a diameter of 28 mm and a thickness of 5 mm. All tests were performed with and without lubrication at room temperature in air with controlled humidity or dry nitrogen. The volumetric wear of the disk was determined by measuring the wear track by a surface profilometer.

2.2. *Implantation conditions*

Implantations with carbon, nitrogen, boron, titanium, and co-implantation with titanium and carbon were performed at energies from 50 keV to 200 keV and 600 keV and 700 keV with doses up to several times of 10^{18} cm^{-2}, measured perpendicular to the beam. The current density was between 2.2 µA cm^{-2} and 75 µA cm^{-2}. By cooling or using a low current density, the implantation temperature was kept below 380°C. Before implantation, the punches were degreased and cleaned in an ultrasonic bath using acetone and ethanol or methanol. Figure 1 shows the shape and a cross-section of the punches used. The corners at which the punch normally fails are marked.

Owing to the complicated shape of the punches, excessive sample manipulation during implantation was necessary. Figures 2 and 3 show six different configurations for the implantation. In Fig. 2, the tool rotated with a constant speed; in Fig. 3, the rotation was programmed or implantation was performed from different directions. For the first configuration of Fig. 2, the implantation was divided into two procedures. First the side walls were implanted while the punch rotated with a constant speed during the implantation, and then the punch end (front side) was implanted by tilting the tool by 90°. For the second configuration, the punch was tilted by 45° with respect to the ion beam in order to implant the punch end and side walls at the same time. Configuration 3 is similar to configuration 2. In this case, the punch rotated on a cone with a half top angle of 45°. In configurations 4 and 5, the implantation was performed from three or five different directions. For configuration 4, the punch was additionally tilted by 45° with respect to the ion beam. In the case of configuration 5, the beam penetrated perpendicular to the side walls into the punch. Therefore, an additional implantation into the punch end was necessary. For configuration 6, the punch rotated in about 1 s in steps of 45° and then a relatively short implantation period followed (45–60 s). The programmed rotation was repeated until the desired dose was obtained. By adding up the doses for each implantation direction, a dose of 4×10^{17} cm^{-2} was calculated for the four corners where the punch fails. In this case, the increased sputtering

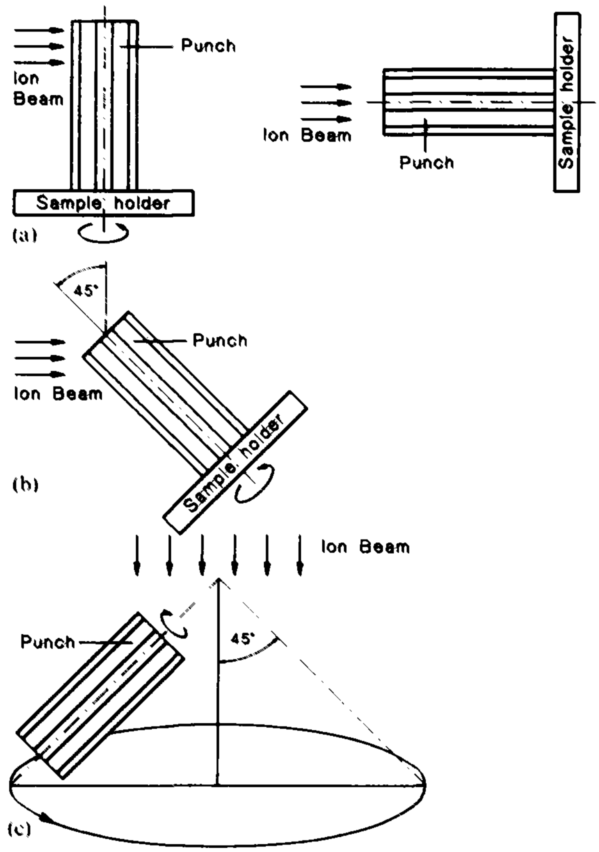

Fig. 2. Implantation configurations with constant rotation. (a) configuration 1; (b) configuration 2; (c) configuration 3.

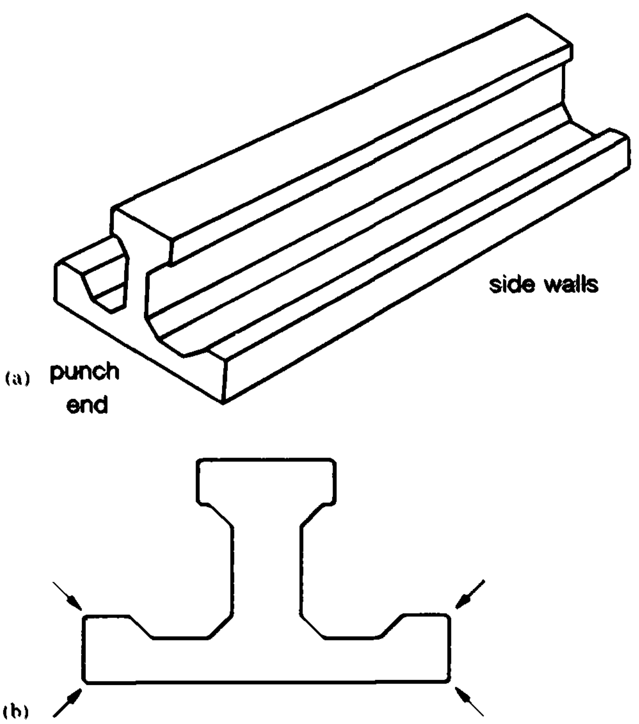

Fig. 1. (a) Drawing of the punches used. (b) Cross-section of the punches. The punch normally failed at the marked corners.

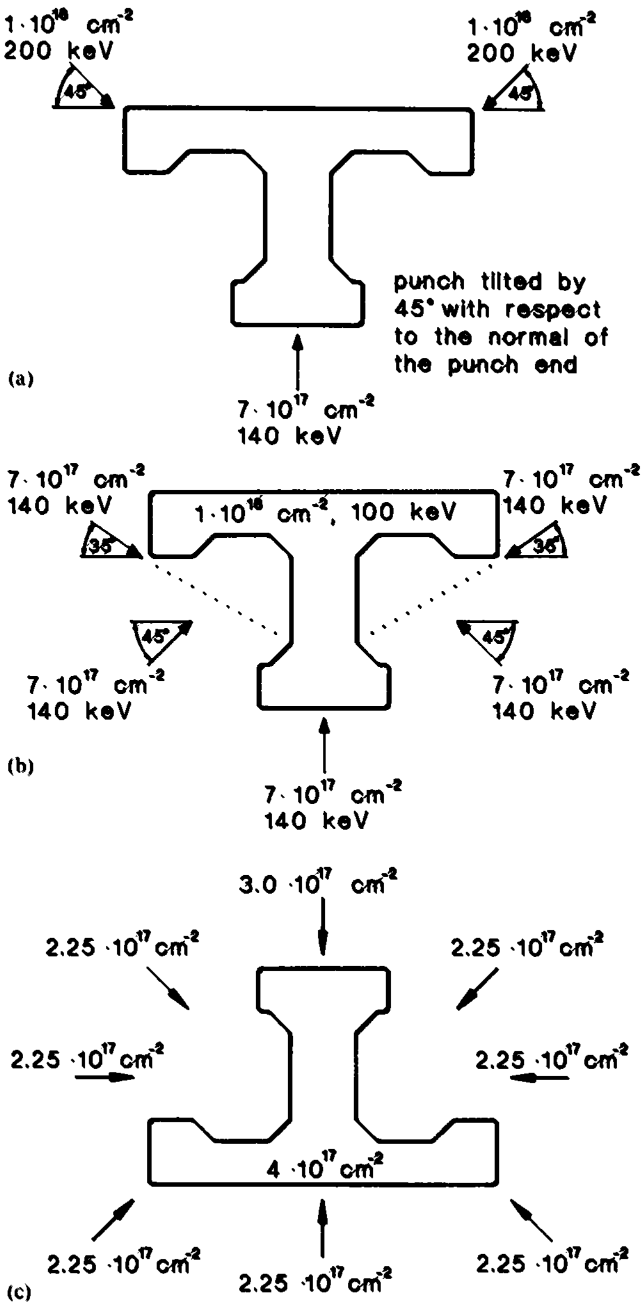

Fig. 3. Implantation configurations with programmed rotation. (a) configuration 4; (b) configuration 5; (c) configuration 6.

yield caused by implantation not perpendicular to the surface was taken into account.

3. Experimental results

3.1. Results of the field tests

In Table 1, the implantation conditions and results of the field tests are presented. The second column shows the configuration (as given in Figs. 2 and 3) while the third and fourth columns show the implantation dose in the side walls or punch end (front side) respectively. The dose was always measured perpendicular to the beam. Therefore, the retained dose for the side walls was at least a factor of 3 lower than the measured value owing to the distribution of the dose over the side walls of the punches. Furthermore, a reduction of the retained dose by sputtering has to be taken into account [6]. If there was a separate implantation of side walls and punch end, both doses and energies are given. For the first test series, the surface roughness of the punches was 0.04 μm. The field tests after implantation of nitrogen, carbon and boron resulted in a large increase in lifetime. For boron implantation, the lifetime rose by a factor of 4.3. Nitrogen implants were also very successful. The implantation of nitrogen with high energy (700 keV, punch 2) yielded a good increase in lifetime (factor of 2.6) at lower doses when compared with punch 4. Additionally, it has to be considered that the punch was tilted by 45°, which means the implanted dose is much lower [6] than 5.6×10^{17} cm^{-2}. A comparison of punches 4 and 5 (100 keV) showed that for punch 5 the dose was too low (half the dose reduces the lifetime by 50%).

Table 2 presents another series of field tests with a new reference sample. This was necessary because of a change in the surface polishing procedure of the punch manufacturer. The new R_a value was 0.14 μm. As a result of the different polishing procedure, the lifetime of the unimplanted reference sample increased by about 20%. Additionally, in some cases a programmed rotation technique was used during implantation to achieve higher doses at the punch corners, the area where the punches usually fail, than by just rotating the punch. For the second series of field tests, the implantation of titanium (punch 3, factor of 2.3) and of nitrogen (punch 2, factor of 2.2 and punch 4, factor of 2.1) showed the best results. For punch 5, the implantation dose was probably somewhat too high. Implantation of boron and carbon (punch 7, punch 8) did not improve the new tools as much as it improved the tools with a surface roughness of $R_a=0.04$ μm (Table 1). The difference in these results compared with the results shown in Table 1 is probably due to the increased surface roughness.

Additional field tests with punches ($R_a=0.14$ μm) either implanted only into the punch end or only into the side walls were performed. For these series, all punches were implanted with boron at 100 keV. Figure 4 shows the results of punch end implantation with doses from 2×10^{17} cm^{-2} to 12×10^{17} cm^{-2}. The punch implanted with a dose of 4×10^{17} cm^{-2} carried out 840 000 strokes, corresponding to an improvement factor of 1.9. Figure 4 indicates a strong dependence of lifetime

TABLE 1. Experimental results of field tests of punches, surface roughness $R_a = 0.04$ μm, ion dose measured perpendicular to the ion beam

Number	Implantation conditions				Strokes to failure	Factor of improvement
	Configuration	Side wall implantation	Punch end implantation	Ion species		
1					360000	
2	3	700 keV, 5.6×10^{17} cm^{-2}		N	922000	2.6
3	3	600 keV, 5.6×10^{17} cm^{-2}		C	784000	2.2
4	1	100 keV, 2.4×10^{18} cm^{-2}	100 keV, 2.4×10^{18} cm^{-2}	N	936000	2.6
5	1	100 keV, 1.2×10^{18} cm^{-2}	100 keV, 1.2×10^{18} cm^{-2}	N	484000	1.3
6	1	100 keV, 1.4×10^{18} cm^{-2}	100 keV, 4×10^{17} cm^{-2}	C	972000	2.7
7	1	100 keV, 1.4×10^{18} cm^{-2}	100 keV, 4×10^{17} cm^{-2}	N	1136000	3.2
8	1	100 keV, 1.4×10^{18} cm^{-2}	100 keV, 4×10^{17} cm^{-2}	B	1540000	4.3

TABLE 2. Experimental results of field tests of punches, surface roughness $R_a = 0.14$ μm, punches manufactured with different polishing procedure compared with Table 1, ion dose measured perpendicular to the ion beam

Number	Implantation conditions				Strokes to failure	Factor of improvement
	Configuration	Side wall implantation	Punch end implantation	Ion species		
1					430000	
2	6	100 keV, 1.875×10^{18} cm^{-2}	100 keV, 4×10^{17} cm^{-2}	N	960000	2.2
3	2	180 keV, 2.5×10^{18} cm^{-2}		Ti	972000	2.3
4	4	140 keV, 1.4×10^{18} cm^{-2} + 200 keV, 1×10^{18} cm^{-2}		N	920000	2.1
5	5	140 keV, 3.5×10^{18} cm^{-2}	100 keV, 1×10^{18} cm^{-2}	N	678000	1.6
6	2	182 keV, 1×10^{18} cm^{-2}, Ti^+ + 50 keV, 1×10^{18} cm^{-2}, C^+		Ti, C	821000	1.9
7	6	100 keV, 1.875×10^{18} cm^{-2}	100 keV, 4×10^{17} cm^{-2}	B	607000	1.4
8	2	180 keV, 4.2×10^{18} cm^{-2}		C	645000	1.5

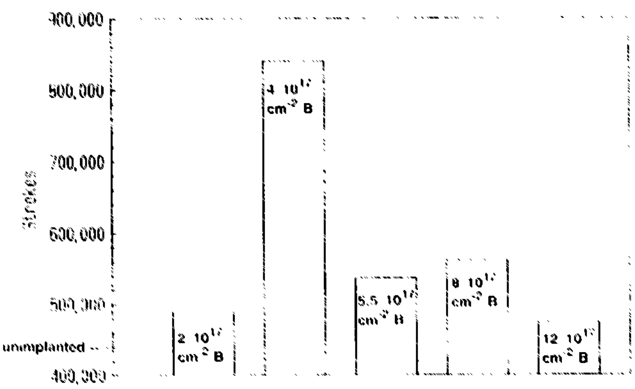

Fig. 4. Results of punch tests after implantation into the punch end, ion species boron, energy 100 keV.

on ion dose. Such a high improvement was only obtained for a dose of 4×10^{17} cm^{-2}.

In contrast to these results, the implantation of the side walls only with a dose of 1.875×10^{18} cm^{-2} (configuration 6) yielded an improvement by a factor of 2.0 (900 000 strokes). So implantation into only the punch end seems to be much more economical, saving implantation time by more than a factor of 4. The disadvantage of this method is that regrinding will remove the implanted layer. A test of a reground punch implanted with nitrogen (configuration 6, energy 100 keV, ion species nitrogen) showed an improvement by a factor of 1.4 after regrinding. So, it is difficult to say whether implantation of the punch end or the side walls is more economical, because the number of regrindings and the improvement factor after each regrinding are important. This was not investigated in this field test.

3.2. *Results of the laboratory tests*

Laboratory investigations as described before (frequency 7 Hz, load 2.2 N, ball material tungsten carbide and AISI 52100, atmosphere air, surface roughness R_a = 0.06 μm) of Vasco Wear after implantation of boron and nitrogen (energy 100 keV, dose 5×10^{17} cm^{-2}) showed, in contrast to the field tests, an increase in wear. Therefore, we changed some of the testing conditions, *e.g.*

frequency and atmosphere, and investigated boron- and nitrogen-implanted Vasco Wear again.

Measurements with the three frequencies 2 Hz, 7 Hz, and 10 Hz corresponding to mean velocities of 8 mm s^{-1}, 28 mm s^{-1}, and 40 mm s^{-1} and maximum velocities of about 25 mm s^{-1}, 80 mm s^{-1}, and 120 mm s^{-1} were performed. The velocity of the punch in the field test was 100 mm s^{-1}. In all cases, the increase in wear remained. Some wear measurements were carried out under dry nitrogen. We found no difference between implanted and unimplanted steel. In this case, the wear of the disk was very low and exact measurements were difficult. The field tests were performed with lubrication. Lubrication means that only a small amount of oxygen influences the wear mechanism. Tribometer tests with lubrication yielded no measurable results owing to the extremely low wear. From this result it can be concluded that lubrication is probably one reason for the different wear results.

In all cases no improvement after ion implantation of Vasco Wear steel could be found. Field tests of punches yielded an improvement of lifetime up to a factor of 4.3. This proves clearly that it is often difficult to compare field tests and laboratory wear tests because of the different testing conditions.

4. Conclusions

Implantation of punches with boron, nitrogen, carbon and titanium, and co-implantation with titanium and carbon, resulted in an increase in lifetime up to a factor of 4.3 or, if compared with the reference sample of the second field test, up to factor of 3.6. Owing to the complicated shape of the punches, excessive sample manipulation was necessary and doses higher than 1.8×10^{18} cm^{-2}, measured perpendicular to the beam, had to be used. The surface roughness had a large influence on the increase in lifetime and the improvement caused by a specific ion species. The maximum improvement was yielded for the lowest surface roughness $R_a = 0.04$ µm. Therefore, when performing the implants, punches with low surface roughness ($R_a = 0.04$ µm) should be used. The most successful ion species were boron and nitrogen for the lowest surface roughness used (0.04 µm), and after changing the polishing procedure ($R_a = 0.14$ µm) titanium and nitrogen at medium energies (100–200 keV). It should be taken into account that nitrogen implantation is much cheaper than implantation of boron or titanium. Additionally, it should be mentioned that no data are available for titanium-implanted punches having a R_a value of 0.04 µm. Implantation into the punch end was only successful (improvement factor 1.9) for a dose of 4×10^{17} cm^{-2}. In this case, further tests should be performed. Irradiation only into the side walls also resulted in an increase in lifetime by a factor of 2. It is not possible to say whether implantation only into the punch end or only into the side walls is more economical, because this depends on the number of possible regrindings and on the improvement factor after each regrinding. In laboratory wear tests no improvement by ion implantation could be found. These results prove that it is difficult to compare field tests and laboratory tests because of the different testing conditions.

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