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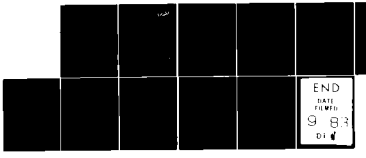

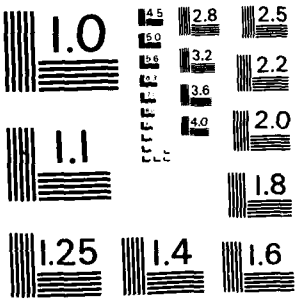

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GC-TR-83-286

MEASUREMENT OF FRICTION AND WEAR ON MODIFIED SURFACES

GEO-CENTERS, INC.

GC-TR-83-286

MEASUREMENT OF FRICTION AND WEAR ON MODIFIED SURFACES

PREPARED FOR
U.S. NAVAL RESEARCH LABORATORY
4555 OVERLOOK AVENUE
WASHINGTON, D.C.
CONTRACT NUMBER N00014-82-C-2092

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MEASUREMENT OF FRICTION AND WEAR ON MODIFIED SURFACES

Dry sliding friction and wear measurements were used to evaluate two implantation processes which increase the C concentration in Ti-implanted steels. In one process, C is implanted into a Ti-implanted steel; in the second Ti is implanted at a lower energy to enhance the efficiency of the vacuum carburization process. Auger spectroscopy and energy-dispersive X-ray analyses were used to analyze the compositions produced by the implantation processes. The low energy (50 keV/ion) Ti-implantation process produced a low friction (μ=0.3), wear resistant surface at a lower fluence ($2x10^{17}/cm^2$) than the dual (C+Ti) implantation process at 50 keV/C ion and 190 keV/Ti ion, respectively. The 50 keV Ti-implantation produced more carburization than the 190 keV Ti-implantation itself; but the dual implant had more Ti, more C, and a greater C/Ti ratio than the low energy Ti implant. We concluded that the improved tribological surface of Ti-implanted steel results from vacuum carburization and not just the presence of excess C.

Ion implantation of metals is moving out of the laboratory and into practice as a surface processing technique for improving the wear life of engineering components. While much emphasis has been placed on N-implantation for improving knives, dies and punches subjected to mild abrasive and adhesive wear environments (1-3), Ti-implantation is receiving considerable attention in the bearing and tool steel community (4,5) because of its ability to reduce friction and wear on hardenable steels subjected to severe wear conditions (6-9).

The improved tribological properties of Ti-implanted steels have been attributed to a unique surface alloy produced by high fluence Ti implantation. The alloy is a mixture of Fe-Ti-C (6-10) with a microstructure shown to be amorphous (8,10). The carbon (C), found in excessively high concentrations near the surface, enters the solid from the vacuum chamber, by a process which can be described as implant-assisted vacuum carburization (8,11). During implantation, sputtering erodes the surface and uncovers implanted Ti, which reacts with residual gases in the vacuum chamber, producing surface carbide species. These carbon atoms then migrate inwards, producing the Fe-Ti-C surface alloy. It is not known, however, whether it is the presence of C itself or the process by which C enters the surface that is responsible for creating this remarkable tribological surface. Dual implants of C and Ti have also produced low wear and low friction surfaces (6,12,13).

The purpose of this study is to investigate two different ion implantation processes which increase the carbon concentration in Ti-implanted steels. Dry sliding friction and wear measurements were used to evaluate the processes and compare them to the original high fluence ($50 \times 10^{16}/cm^2$) high energy (190 keV) process. In one process, separate implantations of Ti and C were performed at energies resulting in similar depth distribution for Ti (190 keV) and C (50 keV) atoms. In the second, Ti was implanted at an energy considerably lower (50 keV) than used previously (190 keV). A recent study of the energy dependence of the Ti implantation process (11) has shown that at lower energies, vacuum carburization is initiated sooner and a more fully carburized layer is produced at a lower fluence. Compositions of surfaces implanted with Ti ions to a fluence of $2 \times 10^{17}/cm^2$ will be presented in order to illustrate the effects of the processing methods on the Ti and C distributions.

Steel disks were metallographically polished, then implanted with Ti, Ti and C, or C ions. The disks were carefully heat sunk to prevent heating by the ion beam during implantation ($T_{Max} < 50^{o}C$). Ti ions were implanted to fluences from 5 to $50x10^{16}/cm^2$ at 50 keV or 190 keV, and C ions to $20x10^{16}/cm^2$ at 50 keV.

Kinetic friction coefficients (μ_k) were measured under rather severe sliding conditions: low speed (0.1 mm/sec), dry sliding contact in air. The geometry was a 1.27 mm diameter ball sliding against an implanted disk flat (both AISI 52100 steel of hardness $R_C \sim 60$). The ball was loaded to 9.8 N (1 kgf), and up to 20 unidirectional passes were made over the same track. The severity of wear produced during sliding was evaluated by optical (differential interference contrast and interferometry) and electron microscopies.

Table 1 summarizes the friction and wear results for the three implantation processing treatments. Low friction ($\mu \sim 0.3$) values required fluences of $50x10^{16}/cm^2$, except for the low energy (50 keV) implantation process, which gave μ_k=0.3 for a fluence of $20x10^{16}/cm^2$. In each of these four low friction surfaces, damage to the "wear" track was negligible. Debris and/or severe wear (>50 nm) was observed on all other tracks (14) except for the Ti+C implant at $20x10^{16}/cm^2$, whose track had a smeared layer but only mild ($\sim$20 nm) wear. This dual implanted surface displayed stick-slip in its friction ($\Delta\mu_k \pm 0.1$); moreover, similar friction and wear behavior resulted when the order of implantation was reversed (i.e. C first, then Ti). By way of comparison, nonimplanted and C (alone) implanted disks had high μ_k max values, 0.6 and 0.7, respectively, and severely damaged wear tracks. Thus, while C implantation somewhat improved the friction and wear behavior of the Ti implanted to $20x10^{16}/cm^2$ at 190 keV, the low energy implant at the same fluence produced a surface as good as the 190 keV Ti implant (with or without C) at $50x10^{16}/cm^2$.

The effects of the three processing treatments on the composition of the implanted surface are revealed in composition vs. depth profiles of the three disks implanted with Ti to $20x10^{16}/cm^2$ (i.e. those of column 2 of Table 1). Composition vs. depth profiles were obtained by Auger spectroscopy with ion milling and interferometry; quantitative analysis of Auger data is based on reference compounds (6,8). Figure 1 presents profiles of Ti and excess C (the 4 at.% of C found in the bulk alloy has been subtracted out). The high-energy implant (disk 1) in Figure 1(a) shows a Ti profile which peaks at about 60 nm and a vacuum carburized layer about 50 nm deep. The non-Gaussian shape of the Ti profile indicates that the surface was sputtered during implantation (15). The dual implant (disk 2) in Figure 1(b) shows a similar Ti profile with implanted C and Ti overlapping one-to-one. (The concentration of Ti in disk 2 is about 20% less than in disk 1 because implanted C dilutes the Fe-Ti alloy.) The low-energy implant (disk 3) in Figure 1(c) also shows a sputtered Ti profile, peaked nearer the surface, and a more fully carburized layer than the high-energy implant, disk 1.

The composition profiles shown in Figure 1 are readily explained in terms of implanted ion ranges (16), sputtering (15) and vacuum carburization (11) effects. At low energies, the Ti range profile is shallower and the peak concentration is larger than at high energies. At a fluence of $20x10^{16}/cm^2$, more of the shallow, low-energy Ti implants were removed than the more deeply penetrating high-energy Ti implants by sputtering during the implantation process. (The sputtering rate of steel should be nearly the same at energies of 50 keV and 190 keV (17).) However, carburization occurred sooner with the 50 keV Ti implantation because the Ti atoms reached the surface sooner. Thus, in the low-energy Ti implant, we observed less Ti, a shallower Ti distribution with a higher peak concentration, and a more concentrated carburized layer.

Energy dispersive X-ray analysis (EDX) of Ti in the three disks, presented in Table 2, confirmed that a smaller percentage of Ti was retained by the low-energy implant (disk 3) than in the high-energy implants, disks 2 and 1. Retained Ti doses were also determined by graphical integration of Figure 1 and agree to 15% with the EDX values in Table 2. Doses of incorporated C were also obtained by graphical integration. The C to Ti dose ratios for the three disks are listed in Table 2. It is clear from Figure 1 and Table 2 that the low-energy implant (disk 3) was more carburized than the high-energy implant (disk 1), but had less C, less Ti and smaller C/Ti ratio than the dual implant (disk 2). The low-energy implant also had a larger peak concentration than the high-energy implant (32 at.% vs. 22 at.%); however, previous studies have indicated that Ti without sufficient C has a deleterious effect on friction and wear (8,14). We therefore believe that the larger peak Ti concentration obtained by low energy implantation did not play a significant role in the friction behavior; this, however, needs further investigation.

In summary we have evaluated two ion implantation processes which increase the C concentration in Ti-implanted layers above that of the original treatment. Dry sliding friction and wear studies have demonstrated that a low-energy (50 keV) Ti implant can produce a superior tribological surface than a dual implant (Ti at 190 keV plus C at 50 keV) at a lower fluence. A comparison of the compositions of the implanted layers showed that a 50 keV-implanted surface had a more fully carburized layer than a 190 keV-Ti implanted surface, but less C, less retained Ti, and a smaller C to Ti ratio. It thus appears that the C concentration alone is not a controlling factor in the tribological behavior of the Fe-Ti-C layer. More likely, it is the Fe-Ti-C layer produced during the vacuum carburization process which imparts the tribological improvement.

In conclusion, we have found that a vacuum carburized layer is more effective than implanted carbon in forming a superior tribological surface Ti-implanted steel. The fluence required to produce a fully carburized layer decreases as the energy of the implanted Ti decreases. This result is of great practical importance for the ion implantation processing of materials: lower fluences reduce production time and lower energies cut down beam heating problems. It also suggests that if sequential implants are to be performed at several energies (13), e.g. to produce more uniform composition vs. depth profile, that the lowest energy implants should be done first. Dual implants of C and Ti had a somewhat beneficial effect in a bearing steel. We suggest they may prove even more valuable in softer steels where friction reduction by the Ti-induced carburized layer and solid solution strengthening by the C might combine to improve tribological behavior.

Table 1. Maximum Friction Coefficients and Wear Track Damage (n-none; m-mild; s-severe) for Three Ti-Implantation Processes as a Function of Ion Energy and Fluence.

Process	Energy (kev)	Fluence ($x10^{16}/cm^2$) 5	20	
Low-Energy Ti	50	0.6/s	0.3/n	0.3/n
High-Energy Ti	190	0.8/s	0.8/s	0.3/n
Dual Implant: Ti	190	0.7/s	0.5/m	0.3/n
C	50			

Table 2. Retained Ti Dose and C/Ti Ratio for Three Disks Implanted to $2 \times 10^{17}/cm^2$.

	High-Energy Ti Disk 1	Dual Implant Disk 2	Low-Energy Ti Disk 3
Retained Ti ($\pm 1 \times 10^{16}/cm^2$)[a]	13	13	9
C/Ti Ratio	0.060	1.0	0.23

a. By EDX, calibrated against a Ti-implanted steel (5×10^{16} Ti/cm^2 at 190 keV) for which the retention was observed to be almost 100%.

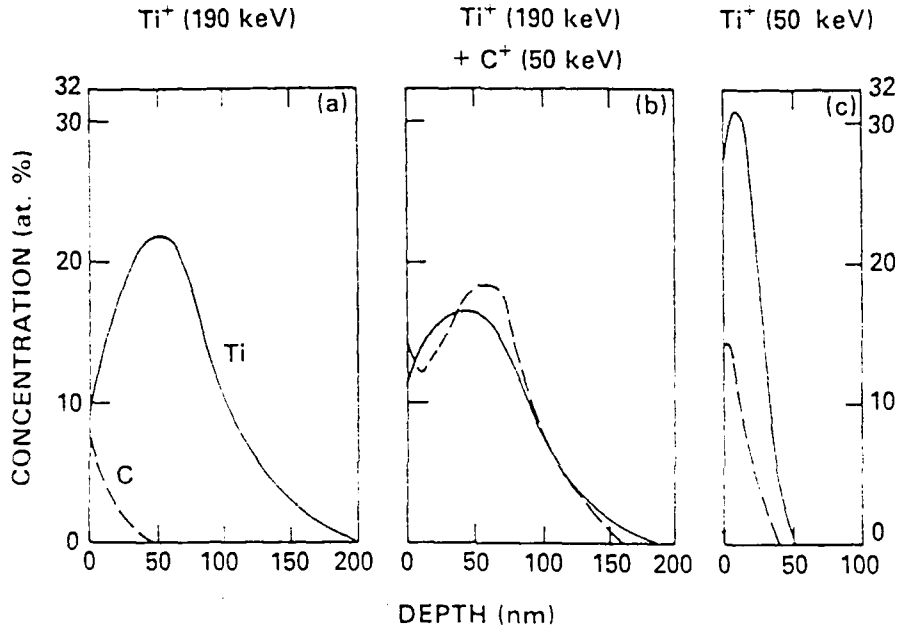

Figure 1. Auger composition vs. depth profiles of Ti and excess C (i.e. above bulk 4 at.%) in 52100 steel implanted to a fluence of 2×10^{17}/cm with (a) disk 1: Ti^+(190 keV); (b) disk 2: Ti^+(190 keV) + C^+(50 keV); (c) disk 3: Ti^+(50 keV).

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GEO-CENTERS, INC.
ANALYSIS OF CONTRACT REVENUES
FISCAL YEARS 1980, 1981, & 1982

PROJECT NO.	AGENCY	YEAR		
		1980	1981	1982
~~121~~	NSWC	$531		
~~136~~	ARRADCOM	$409		
~~140~~	DNA	$-322		
~~141~~	DNA	$8958		
~~144~~	~~COE~~	~~$-49~~		
~~147~~	HQDOE/DOE	$10142	$112	
149	USGS	$788		
~~152~~	ARRADCOM	$45065		
~~153~~	ARRADCOM	$6136		
158	[illegible]	$51394	$137349	$315525
162	[illegible]	$27876	$55931	
163	EG&G	$416		
164	NOSC	$44926	$43251	
165	ONR	$47086	$32796	$1561
166	NRC	$11776		
~~167~~		~~$-20858~~		
168	DOE	170358 ~~$77534~~	$490228	$94808 66257
169	INEL	$73431	$-116	
171	NRC	67158 ~~$8857~~	$83431	$13497
173	NESEC/DOE	$13112	$13112	
176	USGS	$17694	$63574	
180	NRL	$11016	$114797	$143428
182	NEL	$44770	$85938	$48088
183	ARRADCOM		$3089	$77394
184	NRL	$24601	$62084	$8104
185	Partial Withdrawn NRL	$28066		
187	ARRADCOM	$495	$9413	$75676
188	INEL	$16002	$134044	
192	TMI	$37355		
193	NESEC	$9988	$2231	
195	TMI	$4450	$-5	
200	EG&G	$5046	$19143	
201	TMI	$3494		
202	EG&G Idaho Inc.	$23238	$8608	
204			~~$18269~~	
209	NELC/NOSC		~~$38432~~	$89405
212	TMI	$3089		
217	[illegible]		$19246	
218	DNA		$4851	
219	NOS		$22045	$1351
220			$45430	$67193
224				$42840
225	[illegible]		$31594	
228	EG&G		$34960	
229			$48048	$41517
230	EG&G		$14806	
232	EG&G		$5072	
235	INRL		$2000	
242	DNA		$1972	$36646
244	NRL		$8486	$514
246	[illegible]		$21825	

251	Battelle		$909	
255	MANFORD			$50138
256	RICHLAND			$49431
258	INEL		$308	$16846
260	NRL			$30437
261	NRL		$1000	$44250
262	INEL		$4422	$17490
263	NRL		$9600	
264	INEL		$18352	$14503
266	NRL Cov			$82418
267	INEL			~~$20532~~
268	LANL			$20000
269	NRL			$65700
270	INEL		$972	$23653
272	NRL - E Sy			$68432
273	DARPA			$14696
281	NRL - Litchfield			$40811
~~282~~				~~$246~~
286	NRL - Frew			$61519
287	NPRC			$15341
288	NRL - Litchfield			$9511
289	EGG			$8375
291	NRL			$109227
292	EGG			$2375
293	EGG			$33697
295	EGG			$75116
298	EG [illegible]			$5000
299	[illegible]			$32040
302	EGG			$35726
320	[illegible]			$1701
323	[illegible]			$8685
331	EGG			$20000
332	EGG			$15000
336	NRL			$20416
337	NRL			$41687
338	DARPA			~~$9758~~
~~339~~	EGG			
341	GTE - Sylvania			$4730
~~347~~	~~EGG~~			
356	EGG			$3067
362	EGG			$3065
363	INEL			$3671
999	[illegible]	$12450	$7517	$1967
TOTALS		$649942	$1741334	$2219827

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