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NCT Report No
5090/664

Advanced Tribological Coatings For High Specific Strength Alloys, R&D 5876-MS-01

Contract DAJ A45-87-C-0044
Final Report

92-30604

NATIONAL CENTRE OF TRIBOLOGY

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Advanced Tribological Coatings For High Specific Strength Alloys, R&D 5876-MS-01

Contract DAJ A45-87-C-0044

Final Report

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SUMMARY

Titanium alloys offer significant advantages over steels for aerospace applications (particularly space applications) because of its high specific strength. They are, unfortunately, not generally suitable for tribological applications because of their low hardness and tendency to gall.

In an attempt to identify and develop coatings or surface treatments for use on titanium alloy precision gears, the National Centre of Tribology has examined many different treatments. The objective of this work was to improve the tribological performance of titanium alloy by new & emerging wear resistant surface coatings.

Most of these treatments failed a preliminary screening test on a reciprocating tribometer using a maximum Hertzian contact stress of 1.76 GPa in air. Four treatments which passed this test, Beta Nitrocarburizing, Delta Nitrocarburizing, Carbonitriding and TiN on Delta Nitrocarburized titanium, were optimised and checkĕd for repeatability prior to being tested in nitrogen under the same conditions as the initial screening tests.

Of the successful four treatments, three, Beta Nitrocarburizing, Carbonitriding and TiN on Delta Nitrocarburized titanium, were superior in terms of both friction and wear to the untreated titanium when tested in nitrogen. The TiN on top of Delta Nitrocarburizing being the best in nitrogen. The Delta Nitrocarburizing treatment had a lower coefficient of friction than the untreated titanium in nitrogen, but had a similar wear rate.

The target of producing & testing a surface hardened titanium alloy gear set in vacuum was not achieved, mainly because of the difficulty of producing repeatable surface treatments. This also compromised rolling contact fatigue tests performed at AMTL, Watertown,USA. Nevertheless several promising wear resistant coatings (in terms of depth & surface hardness) have been produced by development of previous 'conventional' thermochemical heat treatments.

CONTENTS

1. INTRODUCTION

The use of titanium alloy instead of steel in aerospace applications is advantageous from a mass, corrosion and specific strength viewpoint. Titanium alloys are invariably softer than steel, exhibit a hexagonal close packed structure (HCP) and because of their reactivity have a very thin oxide layer. As a consequence untreated titanium alloys gall rapidly in tribological applications.

There is a limited number of commercial surface treatments to protect the surface of the titanium. These are invariably based on oxidation or the application of 'thick' spray coatings (eg plasma sprays, detonation guns etc). The latter treatments are not suitable for precision mechanical applications, such a gears or bearings. The former are suitable, but to date have shown very indifferent performance.

The objective of this contract was to develop and test surface treatments suitable for the hardening of titanium alloy precision tribo-components for use in aerospace and space (vacuum) environments. A precision gear was chosen as a typical application.

Attention has been primarily directed at surface hardening by the interstitial diffusion of nitrogen, oxygen and carbon. To offer a significant improvement over conventional steel gear application, a surface hardness of >500 HV and a treatment depth of >50 microns (micrometres), without the need of any post heat treatment operations were identified as key targets. Secondly, attention was directed to the repeatability of those surface treatments identified as most promising, and finally those identified as most promising were tested in an inert atmosphere.

This final report summarises the work performed over the period September 1987 to December 1990 (some of which has been reported in more detail in the six interim reports of this contract).

2. SURFACE TREATMENTS

The surface treatments studied were applied to specimens of IMI 318 (90%Ti, 6%Al, 4%V), cut from plate. The plate was either in the annealed condition or in a hardened & ground condition. Further sample sets, each consisting of 4 rods for rolling contact fatigue testing (at AMTL, Watertown, USA) and 6 pins and 2 discs for the NCT vacuum test rig, were prepared using the 'best' four treatments. The sample numbers and corresponding surface treatments, together with the reports in which details were given, are listed in Table 1. Full details of the treatments are contained in Appendix 1. Samples HSSA25 & 29 were not returned from the external surface treatment vendor.

HSSA41-43 are multiple delta nitrocarburizing treatments, initially performed in an attempt to ascertain what effect this treatment had on the titanium alloy, and subsequently used to optimise the treatment time. HSSA44-48 were sample plates treated at the same time as the rolling contact fatigue specimens.

Table 1: Sample Number Allocated to Surface Treatments.

Sample Number	Surface Treatment	Original Report
HSSA1	Annealed	5th
HSSA2	Precipitation hardened	5th
HSSA3	Plasma Nitrocarburized 1#	5th
HSSA4	Beta Nitrocarburized	5th
HSSA5	Ion Implanted (N+) 1#	5th
HSSA6	Ion Implanted (N+) 2#	5th
HSSA7	Hard Anodised 1#	5th
HSSA8	Hard Anodised 2#	5th
HSSA9	Plasma Nitrocarburized 2#	5th
HSSA10	Hard Anodised 3#	5th
HSSA11	Hard Anodised 4#	5th
HSSA12	Plasma Nitrided 1#	5th
HSSA13	Plasma Nitrided 2 #	5th
HSSA14	Delta Nitrocarburized 1#	5th
HSSA15	Nitrox 1#	5th
HSSA16	Pack Aluminised 1#	5th
HSSA17	Nitrox 2#	5th
HSSA18	Nitrox 3#	5th
HSSA19	Pack Aluminised 2#	5th
HSSA20	Carbonitrided 1#	5th
HSSA21	Diamond-like Carbon (DLC)	5th
HSSA22	TiN Reactive Sputter	5th
HSSA23	TiN/HfN Multilayer	5th
HSSA24	Pack Aluminised 3#	5th
HSSA26	HT plasma nitriding	6th
HSSA28	Lucas Nitrotec	Final
HSSA30	Beta nitrocarburized 2#	6th
HSSA31	Delta nitrocarburized 2#	6th
HSSA32	Carbonitrided 2#	6th
HSSA33	Pack Aluminised 4#	Final
HSSA34	Carbonitrided 3#	Final
HSSA35	B Nitrocarburized + TiN (SIP)	Final
HSSA36	D Nitrocarburized + TiN (SIP)	Final
HSSA37	B Nitrocarburized + TiN (Arc)	Final
HSSA38	D Nitrocarburized + TiN (Arc)	Final
HSSA39	HSSA30 Heat Treated	Final
HSSA40	HSSA31 Heat Treated	Final
HSSA41	Delta Nitrocarburized (2hrs) 3#	Final
HSSA42	Delta Nitrocarburized (4hrs) 4#	Final
HSSA43	Delta Nitrocarburized (6hrs) 5#	Final
HSSA44	Plain Titanium	5th
HSSA45	Beta Nitrocarburized 3#	Final
HSSA46	Delta Nitrocarburized 6#	Final

3. SURFACE ROUGHNESS MEASUREMENTS

Surface roughness is an important parameter in determining the specific film thickness in liquid lubricated lubricant applications. The performance & life of dry lubricants such as sputtered MoS_2 is also closely related to surface roughness. To check for any potential change in surface roughness with the treatments, all sample plates were measured using a Talysurf 6 profilometer, and the values of R_a (equivalent to CLA - centre line average).

Figure 1 summarises the R_a measurements of all the samples. The results show that, per plate condition, there is little change in the surface finish (R_a) when the titanium alloy is treated Only aluminising treatment produced significant increases in surface roughness (HSSA19 & 33).

4. METALLOGRAPHIC EXAMINATION

Metallographic sections were prepared for all the treatment samples. From these sections, the structure of the coating was ascertained, and the coating thickness and a microhardness depth profile measured.

4.1 Coating Thickness.

Micrographs and coating thickness results for most of the samples are included in the earlier reports. The micrographs from those samples not previously reported in the interim reports are included in Appendix 2. The coating thickness of these samples, and the earlier results from those of the treatments which have proved of interest are given in Table 2. Where a sample is not included, no measurable coating thickness was identified either by metallurgically sectioning or by microhardness measurements.

T .e results of the Beta Nitrocarburizing treatments show some variation, particularly in HSSA45 which is not as deep as the earlier samples. This method reveals no differences between any of the Delta Nitrocarburizing treatments, even at high magnification. The second carbonitriding treatment (HSSA32) was markedly different to the earlier result (HSSA20) and had quench cracks visible at the surface of the sample in the metallographic section.

4.2 Microhardness Depth Profile

Microhardness depth profiles were produced by measuring the Vickers microhardness at increasing depth into the sample on the metallographic specimens. The hardness was measured by applying a load of 50N for 15 seconds. The microhardness profiles are summarised in Appendix 3.

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DOCUMENT

6.1

6.2 Results at 20N Load in Air

At this load samples HSSA4, HSSA10, HSSA11, HSSA14 and HSSA20 to HSSA 23 originally showed 'good' performance. Figure 2 summarises the measured wear rates for all test samples. The wear profiles for the most recent samples (HSSA26 to HSSA46) are contained in Appendix 5. The friction coeffïcents were usually in the range 0.3 to 0.4. Only samples HSSA32, HSSA37, HSSA39 & HSSA44 consistently exhibited lower friction coefficients (0.2 to 0.3)

Sample HSSA44 (titanium stock) can be regarded as the baseline performance, any coating exhibiting higher wear can be rejected. At this load HSSA33 and HSSA41 had both higher friction and wear then HSSA44. HSSA26, HSSA32, HSSA73 and HSSA38 showed higher friction; HSSA45 and HSSA46 showed higher wear than the titanium stock.

6.3 Results at 50N Load in Air

Originally, samples HSSA4, HSSA14, HSSA20 & HSSA 22 give low wear rates and reasonable friction coefficients. The measured wear rates for all samples are shown in Figure 3 The wear profiles of the most recent samples (HSSA26 to HSSA46) are contained in Appendix 6. The friction coefficients were usually in the range 0.35 to 0.5, except for samples HSSA30, HSSA35, HSSA 39, HSSA41 (0.2 to 0.3)

At this load HSSA28, HSSA30, HSSA31, HSSA39, HSSA40 and HSSA42 had lower coefficients of friction than the titanium stock. HSSA33, HSSA35, HSSA37, HSSA41, HSSA45 and HSSA46 showed higher wear than the titanium stock. Apart from the first reading, the Beta Nitrocarburized samples (HSSA30 and HSSA45) showed similar friction levels. Of the Delta Nitrocarburized samples, only two pairs, HSSA31 & HSSA42 and HSSA41 & HSSA46, were similar.

6.4 Results in Nitrogen.

The wear measurements of the treatments in Table 3 at 20N & 50N load in nitrogen are summarised in Figure 4 The wear profiles are contained in Appendices 7 & 8.

The coefficient of friction for all the tested samples were the same, or higher, in nitrogen than they were in air. Although the wear rates were generally increased in nitrogen compared with air (HSSA34 markedly so), HSSA30, HSSA36, HSSA43, HSSA45, HSSA47 and HSSA48 had wear rates less than the untreated titanium.

The effect of increasing the load on the coefficient of friction in nitrogen varied from sample to sample. The coefficients of friction of HSSA41, HSSA42, HSSA44, HSSA46 and HSSA48 remained the same; HSSA30, HSSA36 and HSSA43 decreased; whilst HSSA34, HSSA45 and HSSA47 increased. The wear rates were again higher in nitrogen than in air, but only Beta Nitrocarburizing (HSSA30), Delta Nitrocarburizing + TiN (HSSA36) and Carbonitriding (HSSA47) had lower wear rates then the untreated titanium alloy.

6.5 Results at 5N in Vacuum.

Figure 5 summarises the friction measurements of sliding tests performed at 5N load in vacuum (<10-6 torr). These were performed on untreated titanium (HSSA44), Beta Nitrocarburizing (HSSA45) and Delta Nitrocarburizing (HSSA46) using both steel pins and pins manufactured and treated the same as the sample material. Due to the treated samples having warped during treatment, only the friction results are given. The untreated titanium and the Beta Nitrocarburized samples showed no significant change in friction levels between steel and identical pins, whilst the Delta Nitrocarburizing sample had a lower coefficient of friction with a steel pin. The coefficients of friction for untreated and treated titanium increase in the order air, nitrogen, vacuum.

7. DISCUSSION

The majority of the treatments examined were of no practical use, failing at 50N load (1.76 GPa) on the reciprocating tribometer in air. As vacuum is a more severe tribological environment than air, these were not persued. Those which passed in this test in air were: Beta and Delta Nitrocarburizing, Carbonitriding, Reactive Sputter Titanium Nitride, Delta Carburizing plus Titanium Nitride, HT Plasma Nitriding and Lucas Nitrotec.

Of the Beta Nitrocarburized samples examined, HSSA4 and HSSA30 showed promising friction and wear performance but HSSA45 was very different (ie poorer). It is believed that HSSA45 did not perform as well because the case depth was insufficient, being only 20 microns deep instead of between 50 and 70 microns like HSSA4 and HSSA30. Despite this, the Beta Nitrocarburized samples all showed similar friction levels in air and nitrogen. The cause of the variation in the case depth has been identified. HSSA30 also gave reduced wear in nitrogen at 50N load.

Delta Nitrocarburizing has given some variation in its performance. However, as the result of the multiple treatments the cause of this variation has been identified. Although metallography has been unable to find any differences between the different time length Delta Nitrocarburizing treatments, surface hardness measurements clearly show the difference between the different lengths of time of treatment. These measurements indicate that HSSA46 wore because it was not treated for as long as HSSA42 (4 hours).

Surface hardness measurements in the range 10g to 1kg have been established as useful as quality control for Delta Nitrocarburizing. However, nanohardness measurements, which were also made using equipment available at NCT, did not produce as clear-cut a result as the microhardness measurements reported here.

Delta Nitrocarburizing did not perform as well in nitrogen as it did in air, only having a lower coefficient of friction and about the same wear rate as the untreated titanium. However, it is useful in air and is currently being applied commercially.

The initial Carbonitrided sample (HSSA20) showed promising friction and wear performance as well as meeting the targets for surface hardness and treatment depth. However, the second sample HSSA32) proved to have a markedly different metallographic section to the first and was subsequently found to have a higher coefficient of friction. Inquiries at the treatment firm established that HSSA20 was Carburized prior to being Carbonitrided, which HSSA32 was not. Full replication of this treatment provided repeatability in air. This treatment was also one which was better than unprotected titanium in nitrogen.

Reactive Sputter Titanium Nitride (TiN) (HSSA22) showed promising friction and wear performance in air. However, examination indicated that the coating may have been on the verge of break-down when tested at 50N load on the reciprocating tribometer. This would probably have been caused by inadequate sheer strength in the underlying titanium alloy. In an effort to prevent this incipient breakdown by providing support for the TiN, samples were Nitrocarburized prior to being coated with Titanium Nitride applied by both Arc Evaporation and Sputter Ion Plating.

Beta Nitrocarburizing + TiN (HSSA35 (SIP) and HSSA37 (Arc)) proved to be of no use as both of these combinations wore rapidly at 50N load in air. Delta Nitrocarburizing + TiN by both SIP (HSSA36 and HSSA48) and Arc evaporation (HSSA38) proved to be very successful in air. Delta Nitrocarburizing + TiN (Arc Evaporation) was not persued as this combination caused the titanium plate to warp However, one of the two Delta Nitrocarburizing + TiN by SIP (HSSA36) gave the best friction and wear performance in nitrogen of the treatments tested. It is believed that the second sample (HSSA48) only gave a marginal improvement because the underlying Delta Nitrocarburizing was not optimised.

The coefficient of friction for all the tested samples were the same, or higher, in nitrogen than they were in air. Although the wear rates were generally increased in nitrogen compared with air (HSSA34 markedly so); Beta Nitrocarburized, Carbonitrided and Delta Nitrocarburized + TiN gave reduced wear at 50N load. The rate of wear for Delta Nitrocarburizing decreased with increasing length of time of treatment - it, however, remained greater than the untreated titanium. The coefficients of friction increased in the order air, nitrogen, vacuum.

From their results in air, HT plasma nitriding (HSSA26) and Lucas Nitrotec (HSSA28) show promise as potential treatments. These were not persued due to the long period of time these companies had taken to return the samples and the fact that the programme was drawing to a close. Future work could include the investigation of the benefits of these treatments.

8. CLOSURE

This work was aimed at finding suitable surface treatments for titanium precision gears. The target to produce & test a suitable gear combination in vacuum was not achieved because of the difficulty of producing repeatable surface treatments. This also compromised rolling contact fatigue tests at the US Army Materials Technology Laboratory, Watertown USA (Mr R M Middleton), where minute distortions of the rolling contact fatigue specimens (RCF) did not allow representative testing to take place (unacceptable vibration on fatigue tester). Despite this the author is not aware of any other work which has produced such promising coatings (in terms of depth & hardness) by conventional thermochemical heat treatments. Whilst the sensitivity of the subsequent coating to the treatment conditions has been the major stumbling block in this work, the promising nature of many of the treatments is worth of note. In particular Delta and Beta Nitrocarburizing, Carbonitriding and TiN on Delta Nitrocarburizing.. Lucas Nitrotec and HT Plasma Nitriding appear to be potential candidates to this list. The Carbonitriding treatments metthe identified targets of coating depth (>50 microns) & surface hardness (>500HV), but consistent treatments were not achieved within the scope of this contract.

APPENDIX 1: Surface Treatment Descriptions & Details

A1.1 Beta Nitrocarburized

Produces treatment 20 to 70 microns deep with a hardness of about 550 Hv. 2 types of Beta treatment: 'Normal' and 'Alloy'. Difference between these treatments is temperature (typical for 'normal' is 700^{o}C, 'alloy' is higher). There are differences in the post treatment, essentially in the number of tempering cycles performed. The differences seen in the results are probably due to this. A superior quench & tempering procedure has been identified. The Beta process should not distort if the items are stress relieved during manufacture.

Sample History

HSSA4: original sample.

HSSA30: repeat to ensure reproducability.

HSSA39: HSSA30 heat treated, treatment cycle designed to simulate TiN coating run to investigate what, if any, effects this has on the treatment.

HSSA45: sample plate treated at the same time as the rolling contact fatigue specimens.

A1.2 Delta Nitrocarburized

Performed at 600^{o}C. Delta Nitrocarburizing generates a hard alloy near to the surface of the titanium with a thickness <2 microns. Surface hardness measurements clearly show the difference between different lengths of time of treatment. Surface hardness measurements in the range 10g to 1kg have been established as useful as quality control for Delta Nitrocarburizing. Delta Nitrocarburizing is currently being applied commercially.

Sample History

HSSA14: Original sample

HSSA31: Repeat to ensure reproducability.

HSSA40: HSSA31 Heat Treated, treatment cycle designed to simulate TiN coating run to investigate what, if any, effects this has on the treatment.
HSSA41-43: are multiple delta nitrocarburizing treatments (HSSA41 (2hrs), HSSA42 (4hrs), HSSA43 (6hrs)). These were performed to ascertain what effect this treatment had on the titanium alloy, and subsequently used to optimise the treatment time.

HSSA46: sample plate treated at the same time as the rolling contact fatigue specimens.

A1.3 Plasma Nitrocarburized

Similar to nitriding, but the process employs diffusion of carbon as well as nitrogen, to produce a surface layer of carbo-nitrides. Application temperature is around 550^{o}C. Produces a layer less than 2 microns thick.

Sample History.

HSSA3: From solution heat treated feedstock.
HSSA9: From hardened and ground feedstock

A1.4 Lucas Nitrotec

Layer 10 microns thick of hardness 300 Hv. Only one sample tested (HSSA28). Lucas Nitrotec appears to be a candidate to join the list of tribological treatments for titanium alloy.

A1.5 Carbonitride.

Actually carburise followed by carbonitriding. Treatment temperature 900^{o}C. In comparison with beta and delta treatments (which are regarded as controllable) carbonitriding is difficult to control and difficult to reproduce. This process was originally developed for treating large quantities of mild steel for which it is very good. Supplier expects the results to be variable on titanium. Measured layer thickness varied between 100 and 300 microns with a hardness between 650 and 700 Hv.

<u>Sample history</u>
HSSA20 1: Original sample.
HSSA32 2: Repeat of 1.
HSSA34 3: Further repeat.
HSSA47 4: Sample plate treated at the same time as the rolling contact fatigue specimens.

A1.6 Plasma Nitrided

HSSA12 (1), Solution Heat Treated
HSSA13 (2), Hardened and Ground
Analysis revealed poor processing.

A1.7 High Temperature Plasma Nitriding

High Temperature Plasma Nitriding appears to be a candidate to join the list of tribological treatments for titanium alloy. Only one sample produced (HSSA26).

A1.8 Nitrox

Produces a thin (~5 microns) layer with a hardness about400Hv.

<u>Sample History</u>
HSSA15 (1), Hardened and Ground
HSSA17 (2), Solution Heat Treated
HSSA18 (3), Hardened and Ground

A1.9 Hard Anodised

Negligible surface layer found

Sample history
HSSA7 (1), Solution Heat Treated
HSSA8 (2), Hardened and Ground
HSSA10 (3), Solution Heat Treated
HSSA11 (4), Hardened and Ground

A1.10 Pack Aluminising

25 micrometre layer, 340 to 560 Hv.

Sample history
HSSA16 1: Solution Heat Treated
HSSA19 2: Hardened and Ground
HSSA24 3: Hardened and Ground
HSSA33 4: Solution Heat Treated

A1.11 Ion Implantation

Nitrogen ions accelerated into surface in vacuum. Treated layer typically sub-micron in thickness.

Sample history:
HSSA5 1: Solution Heat Treated
HSSA6 2: Hardened and Ground

A1.12 Diamond-like Carbon
(DLC)
HSSA21 1 micrometre Not measured

A1.13 TiN
Reactive Sputter HSSA22
3 microns Not measured

A1.14 Combination Samples
The combination samples (Nitrocarburizing and TiN) were prepared to overcome the perceived faults of the ordinary TiN and TiN/HfN multilayer (film failure due to lack of support for the coating). PVD TiN by two different methods (Sputter Ion Plate and Arc Evaporation) on Beta and Delta Nitrocarburize. Each TiN process laid down a 2 micrometre thick coating on top of the Nitrocarburized plate. The nitrocarburized layer was typical for the Huyton process.

A1.15 TiN/HfN Multilayer
HSSA23 5 microns Not measured

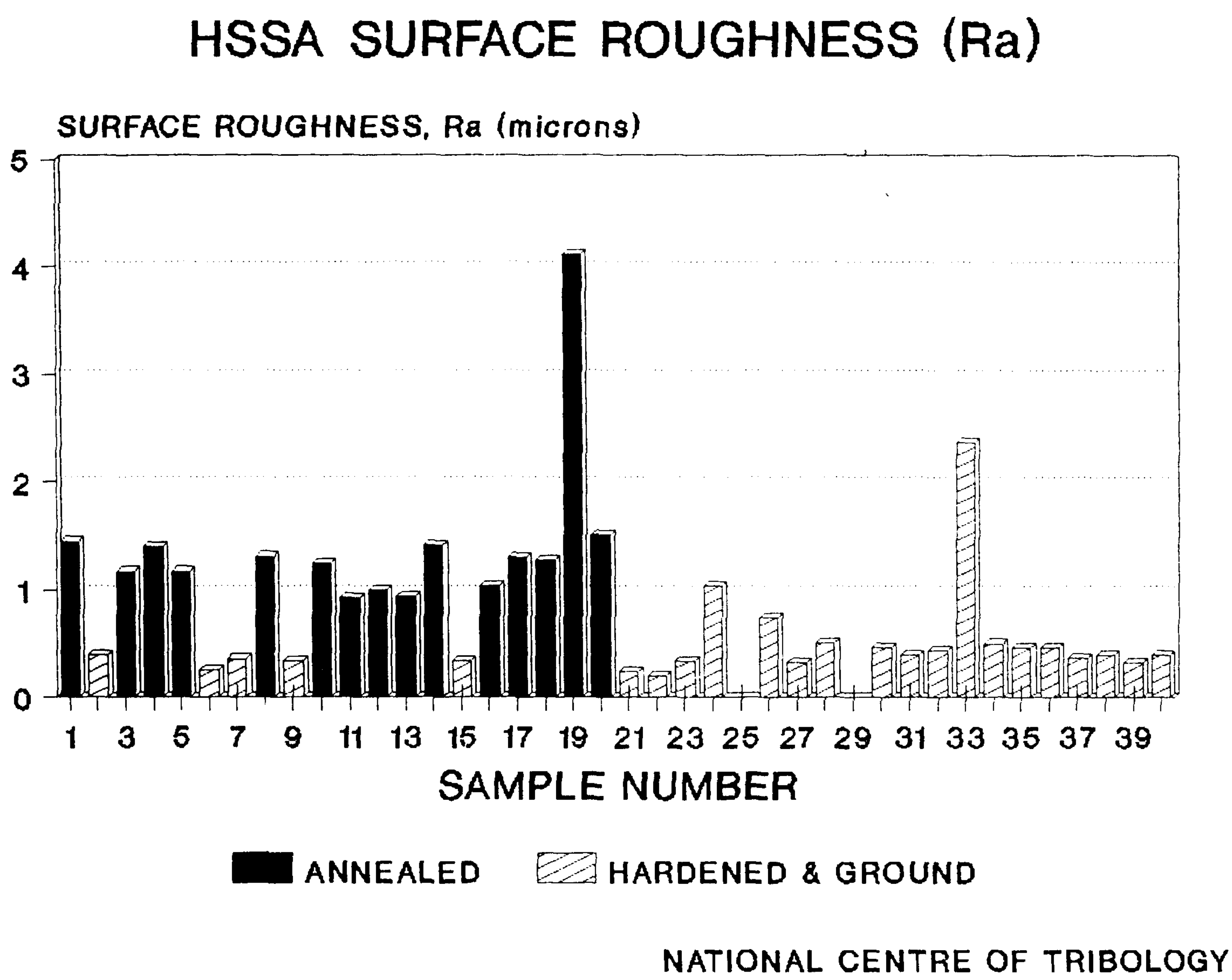
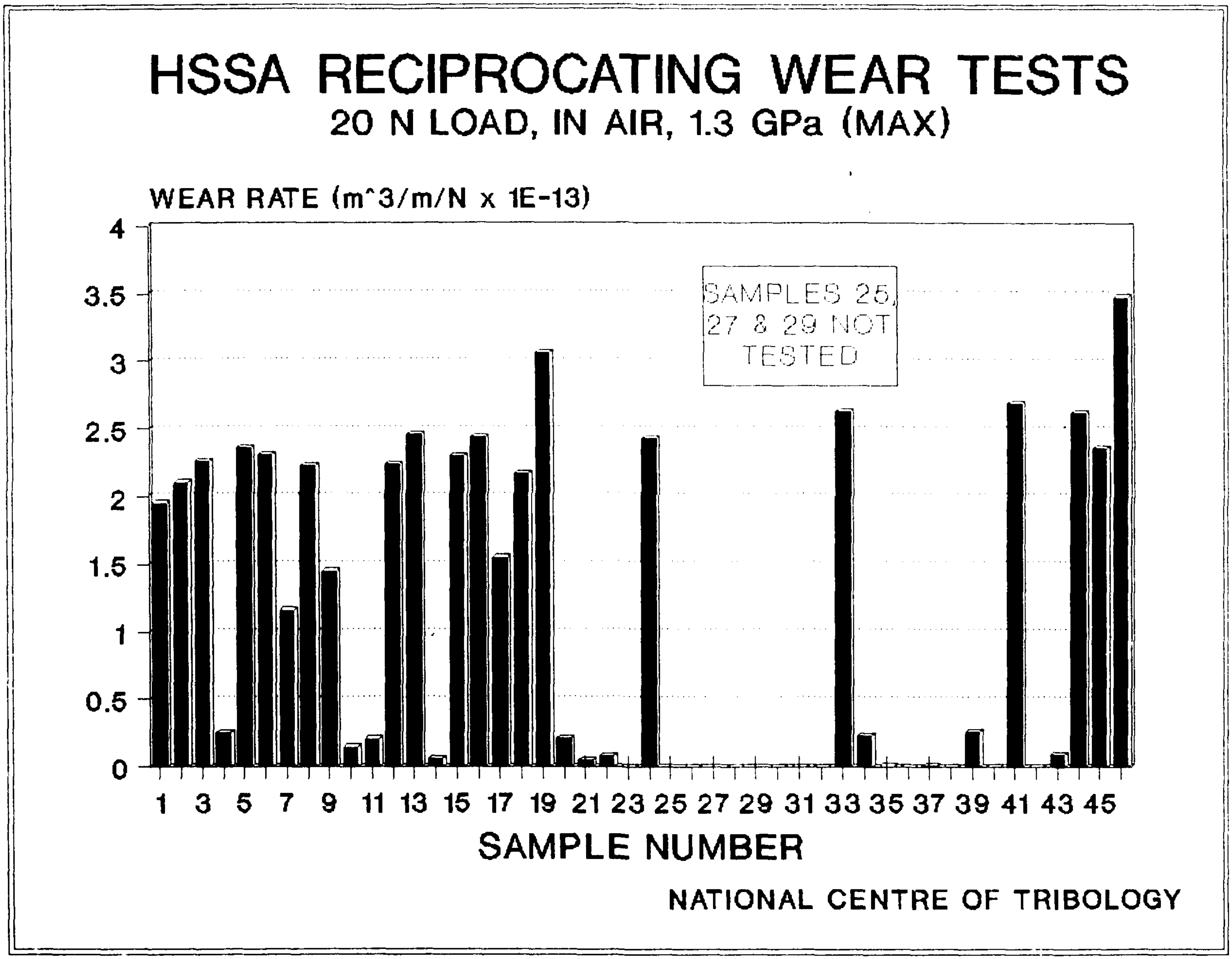

HSSA SURFACE ROUGHNESS (Ra)
SURFACE ROUGHNESS, Ra (microns)
5
4
3
2
1
0
1 3 5 7 9 11 13 15 17 19 21 23 25 27 29 31 33 35 37 39
SAMPLE NUMBER
ANNEALED
HARDENED & GROUND
NATIONAL CENTRE OF TRIBOLOGY

Figure 1



HSSA RECIPROCATING WEAR TESTS
20 N LOAD, IN AIR, 1.3 GPa (MAX)
WEAR RATE (m^3/m/N x 1E-13)
4
3.5
3
2.5
2
1.5
1
0.5
0
SAMPLES 25, 27 & 29 NOT TESTED
1 3 5 7 9 11 13 15 17 19 21 23 25 27 29 31 33 35 37 39 41 43 45
SAMPLE NUMBER
NATIONAL CENTRE OF TRIBOLOGY

Figure 2

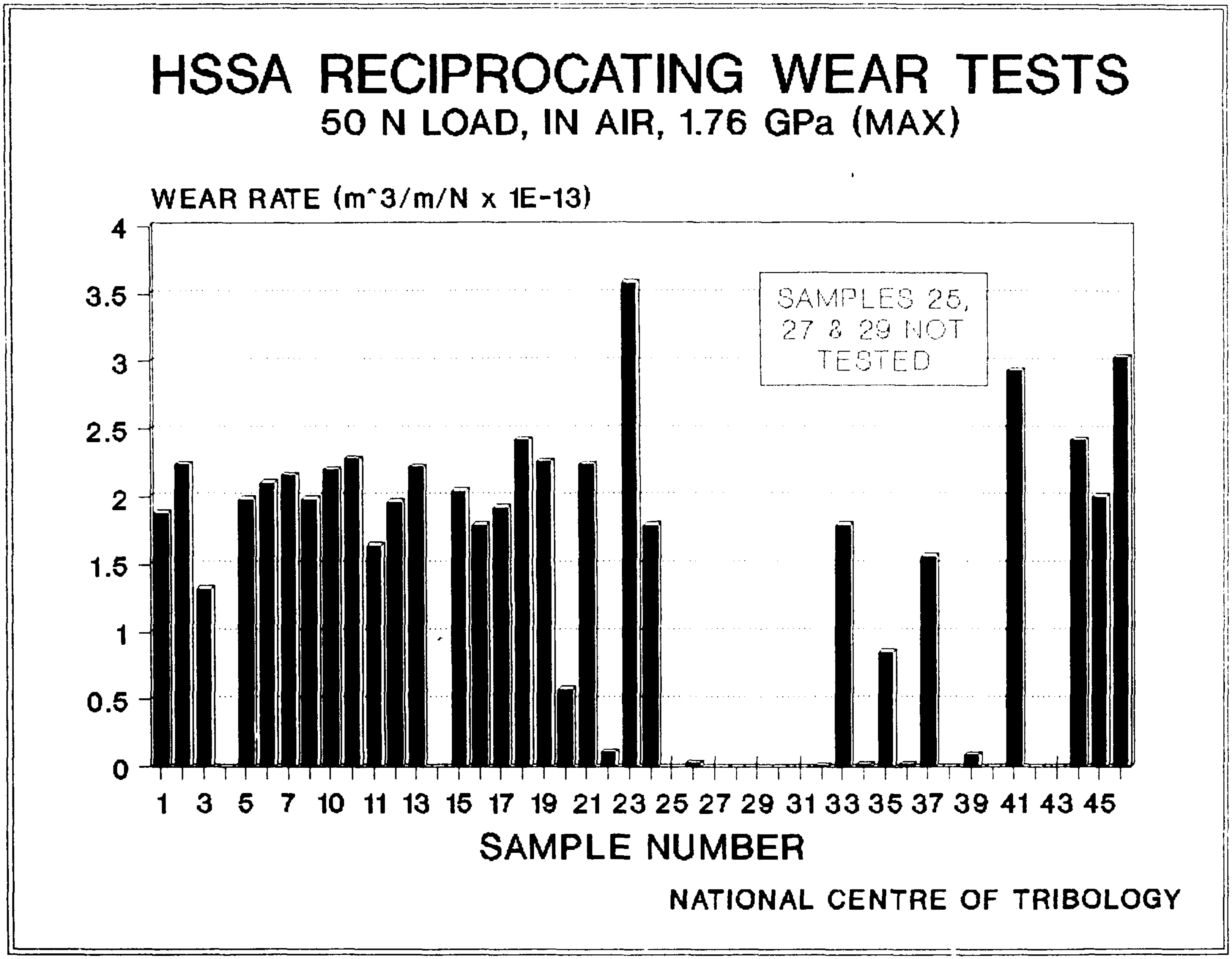

HSSA RECIPROCATING WEAR TESTS
50 N LOAD, IN AIR, 1.76 GPa (MAX)
WEAR RATE (m^3/m/N x 1E-13)
4
3.5
3
2.5
2
1.5
1
0.5
0
SAMPLES 25, 27 & 29 NOT TESTED
1 3 5 7 10 11 13 15 17 19 21 23 25 27 29 31 33 35 37 39 41 43 45
SAMPLE NUMBER
NATIONAL CENTRE OF TRIBOLOGY

Figure 3

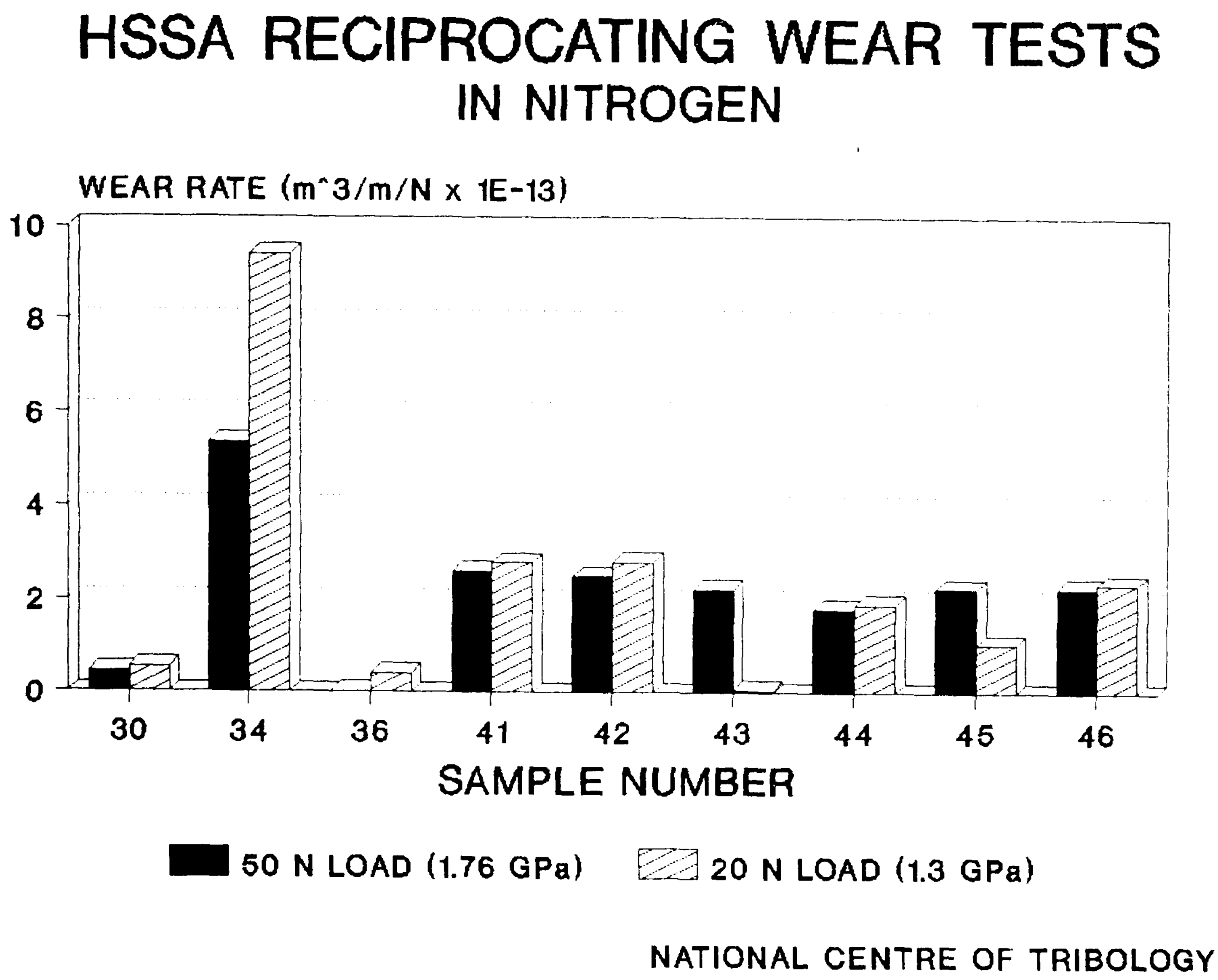

HSSA RECIPROCATING WEAR TESTS
IN NITROGEN
WEAR RATE (m^3/m/N x 1E-13)
10
8
6
4
2
0
30
34
36
41
42
43
44
45
46
SAMPLE NUMBER
50 N LOAD (1.76 GPa)
20 N LOAD (1.3 GPa)
NATIONAL CENTRE OF TRIBOLOGY

Figure 4

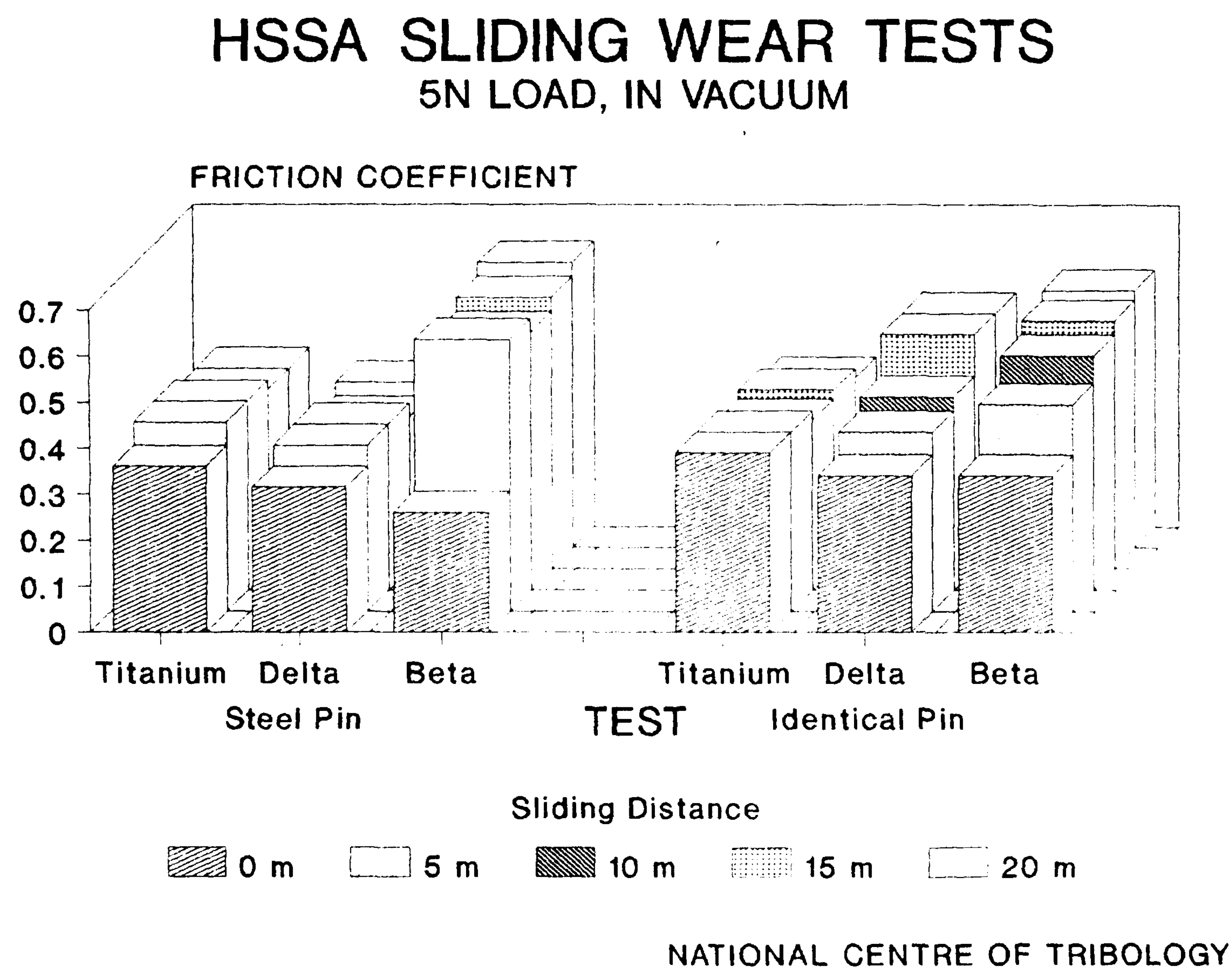
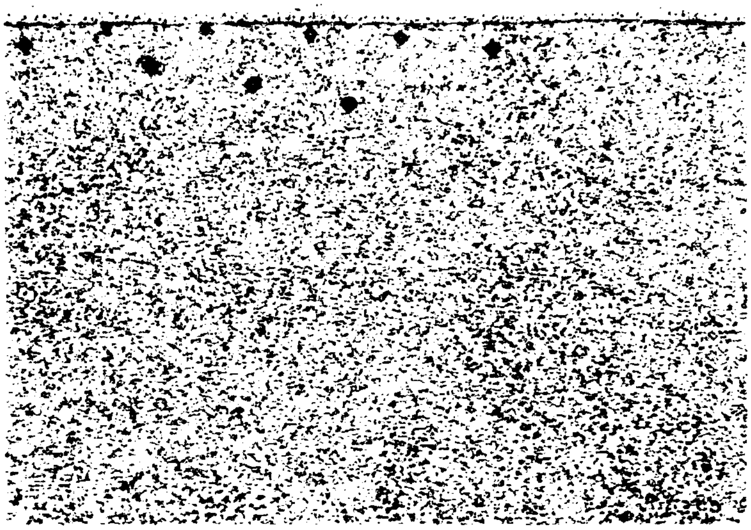

HSSA SLIDING WEAR TESTS
5N LOAD, IN VACUUM
FRICTION COEFFICIENT
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
Titanium
Delta
Beta
Steel Pin
TEST
Titanium
Delta
Beta
Identical Pin
Sliding Distance
0 m
5 m
10 m
15 m
20 m
NATIONAL CENTRE OF TRIBOLOGY

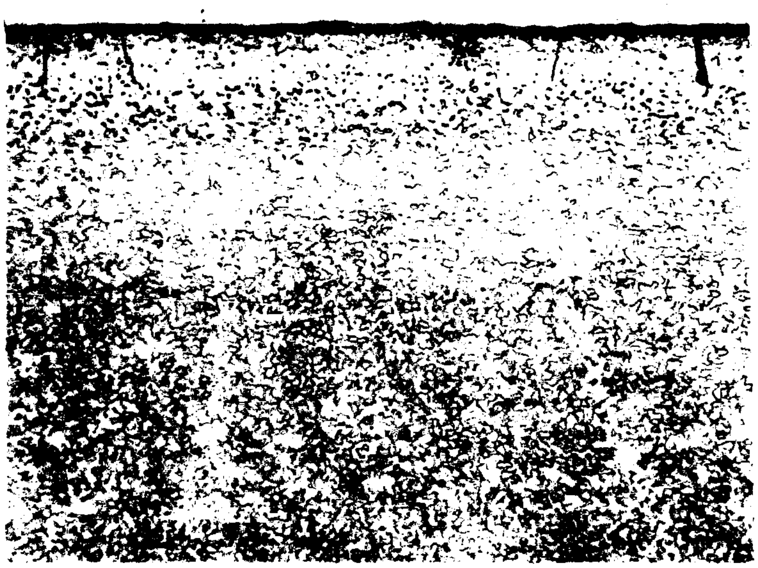
Figure 5

APPENDIX 2: Optical Micrographs of Metallographic Specimens



HSSA28 Lucas Nitrotec (x200)

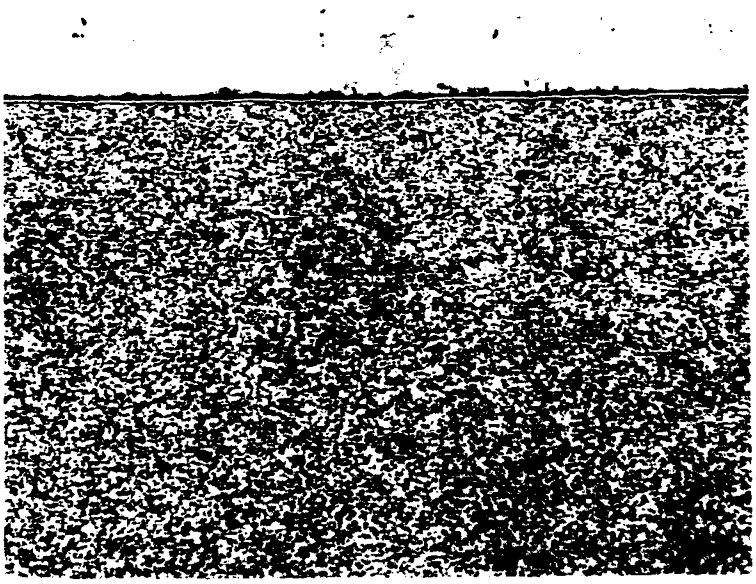
HSSA33 Pack Aluminised 4 (x200)



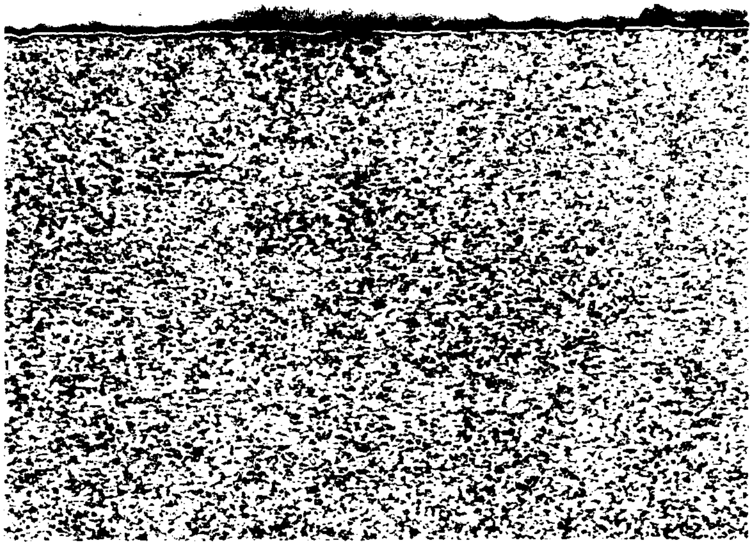
HSSA34 Carbonitrided 3 (x200)

HSSA35 B Nitrocarburized + TiN (SIP) (x200)

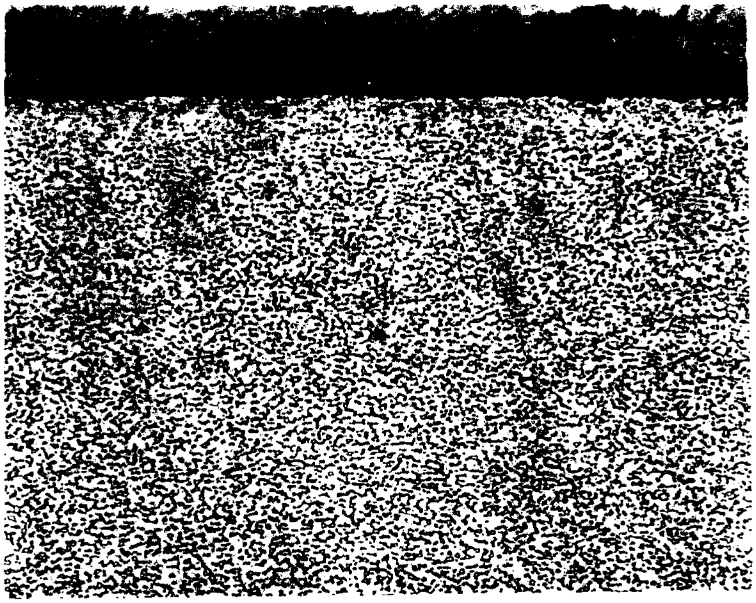
HSSA36 D Nitrocarburized + TiN (SIP) 1 (x200)



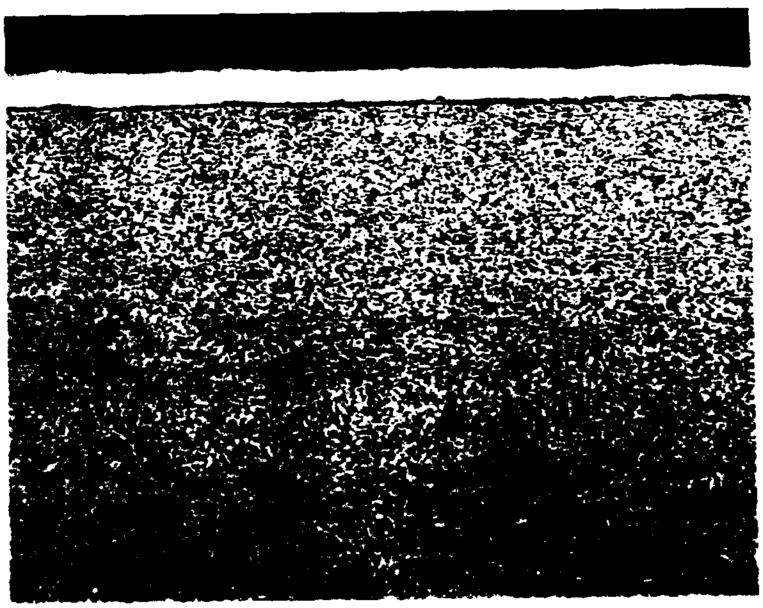
HSSA37 B Nitrocarburized + TiN (Arc) (x200)



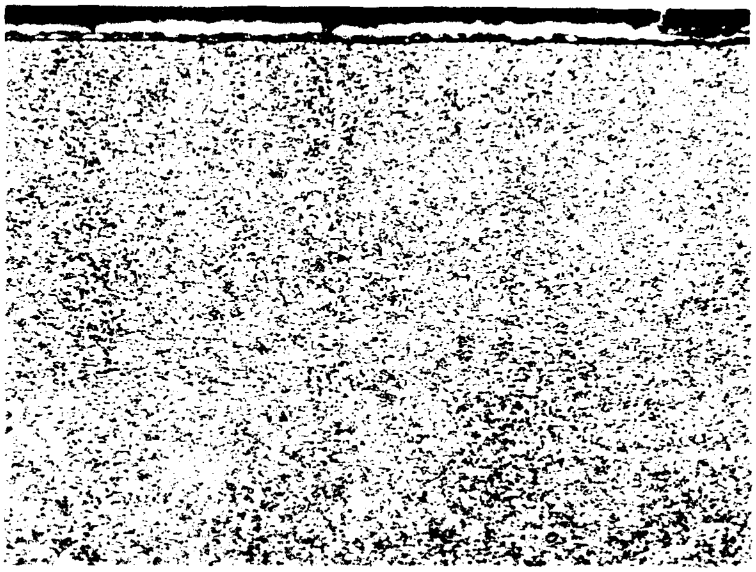
HSSA38 D Nitrocarburized + TiN (Arc) (x200)



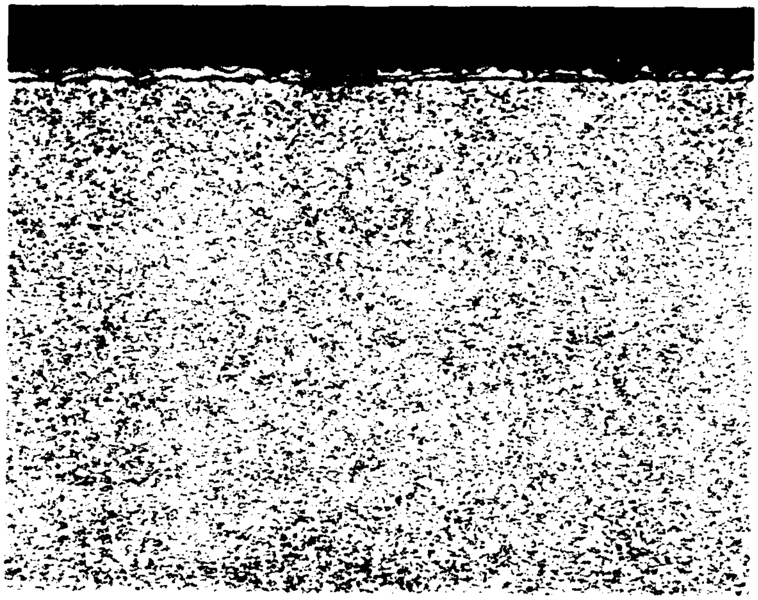
HSSA39 HSSA30 Heat Treated (x200)



HSSA40 HSSA31 Heat Treated (x200)

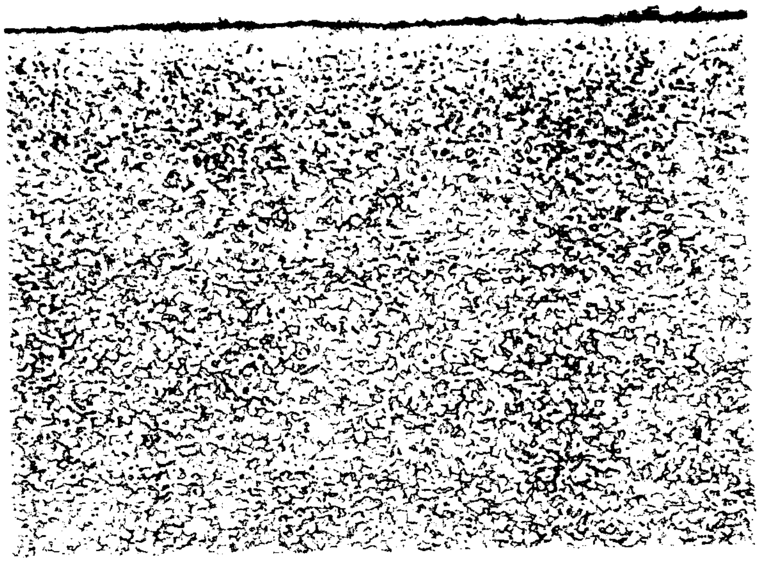


HSSA41 Delta Nitrocarburized (2hrs) 3 (x200)

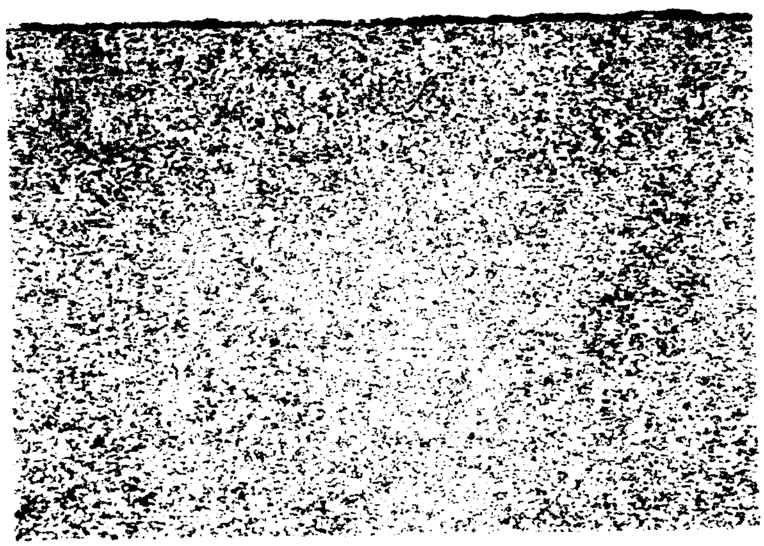


HSSA42 Delta Nitrocarburized (4hrs) 4 (x200)

HSSA43 Delta Nitrocarburized (6hrs) 5 (x200)



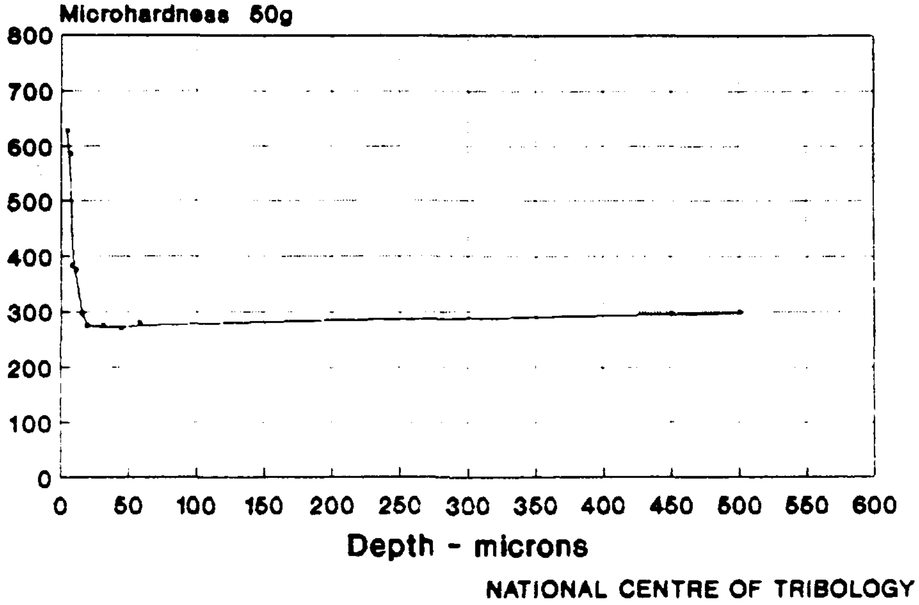
HSSA45 Beta Nitrocarburized 3 (x200)



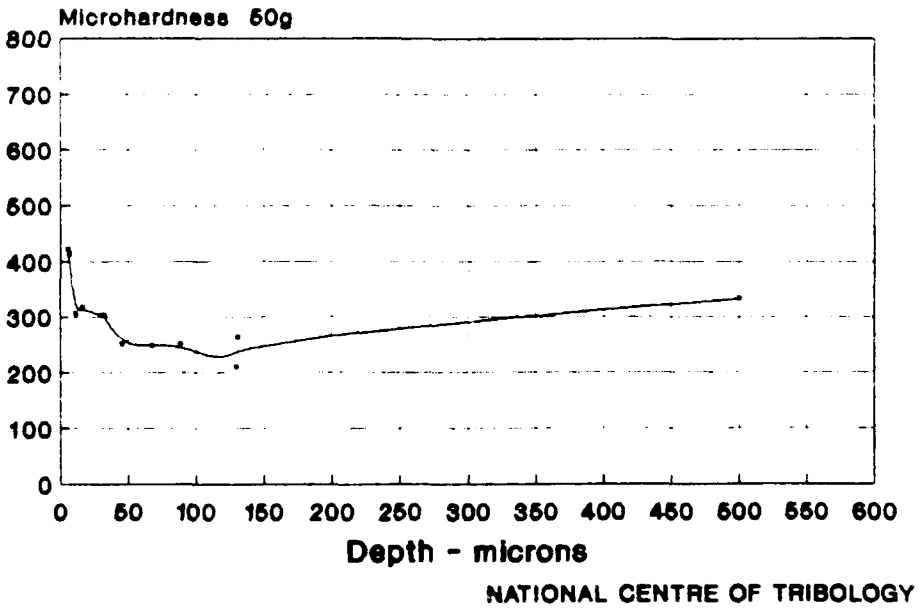
HSSA46 Delta Nitrocarburized 6 (x200)

APPENDIX 3. Microhardness Depth Profiles

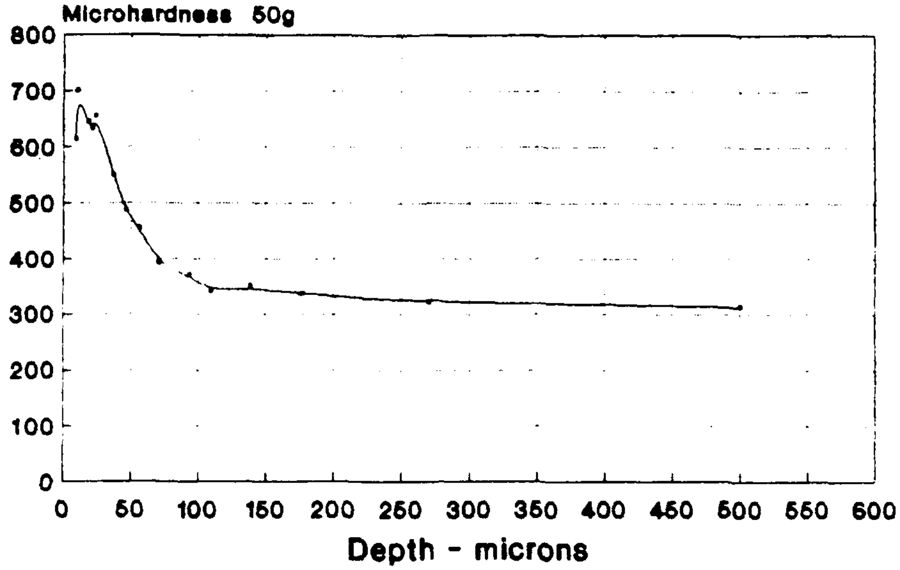
MICROHARDNESS DEPTH PROFILE
HSSA28 LUCAS NITROTEC #1



MICROHARDNESS DEPTH PROFILE
HSSA33/ ALUMINISED #4

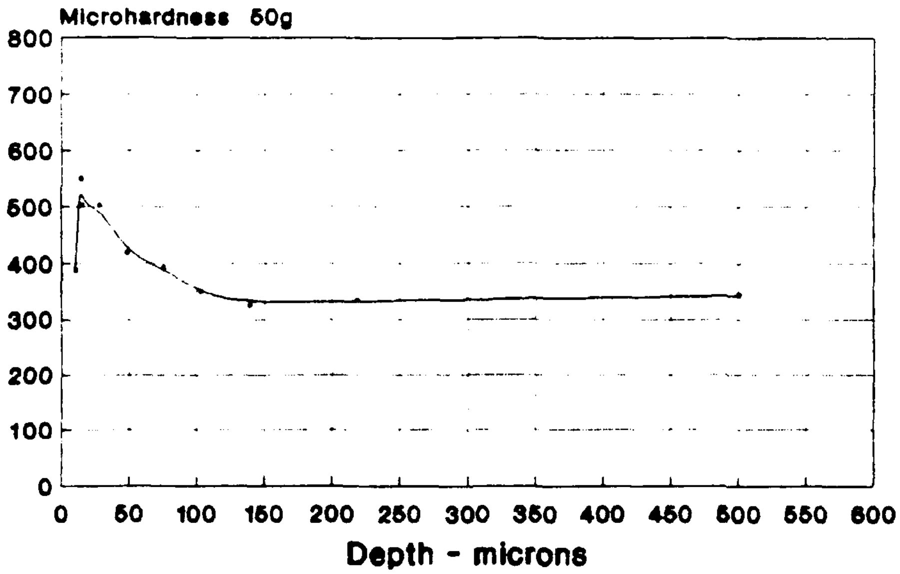


MICROHARDNESS DEPTH PROFILE
HSSA34/ CARBURIZED/ CARBO-NITRIDED #2



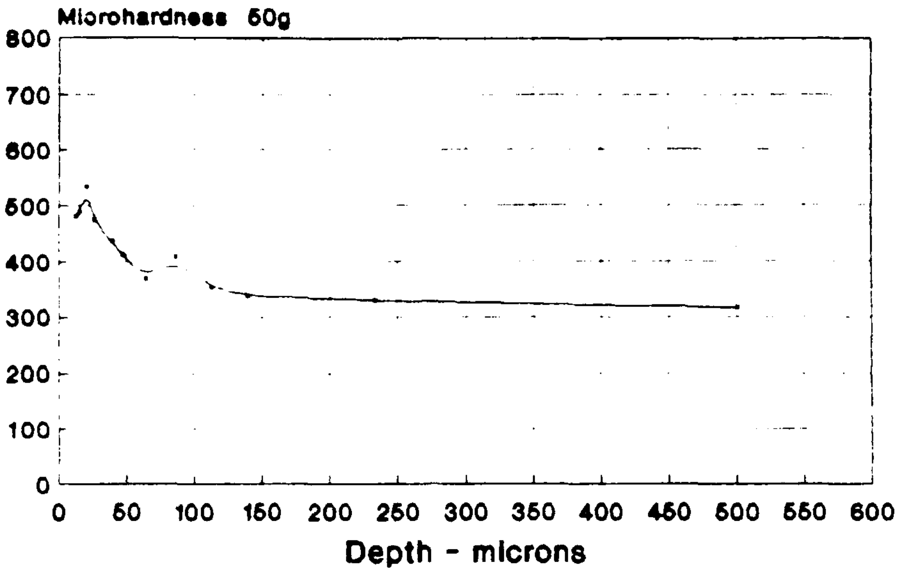
NATIONAL CENTRE OF TRIBOLOGY

MICROHARDNESS DEPTH PROFILE
HSSA35/ BETA NITROCARBURIZED + TiN (SIP)



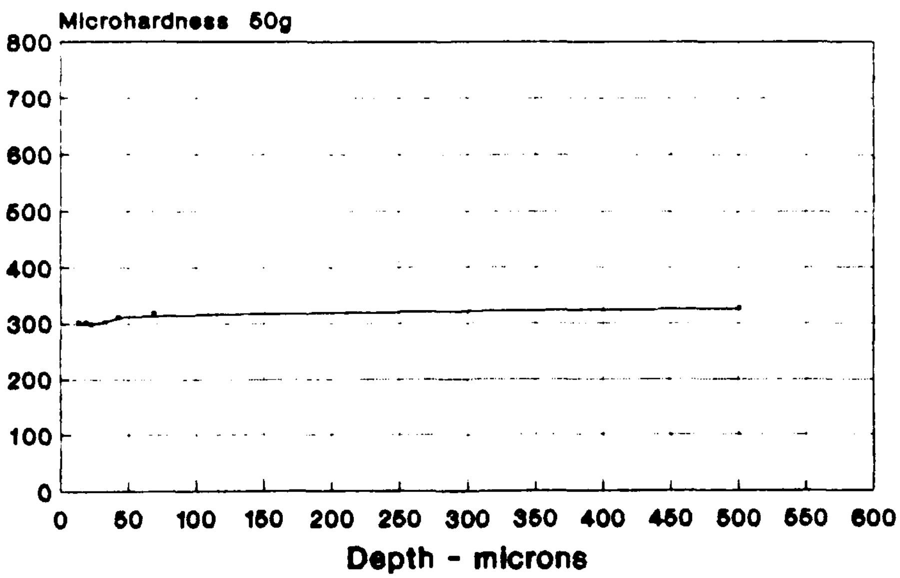
NATIONAL CENTRE OF TRIBOLOGY

MICROHARDNESS DEPTH PROFILE
HSSA36/ BETA NITROCARBURIZED + TiN (AE)



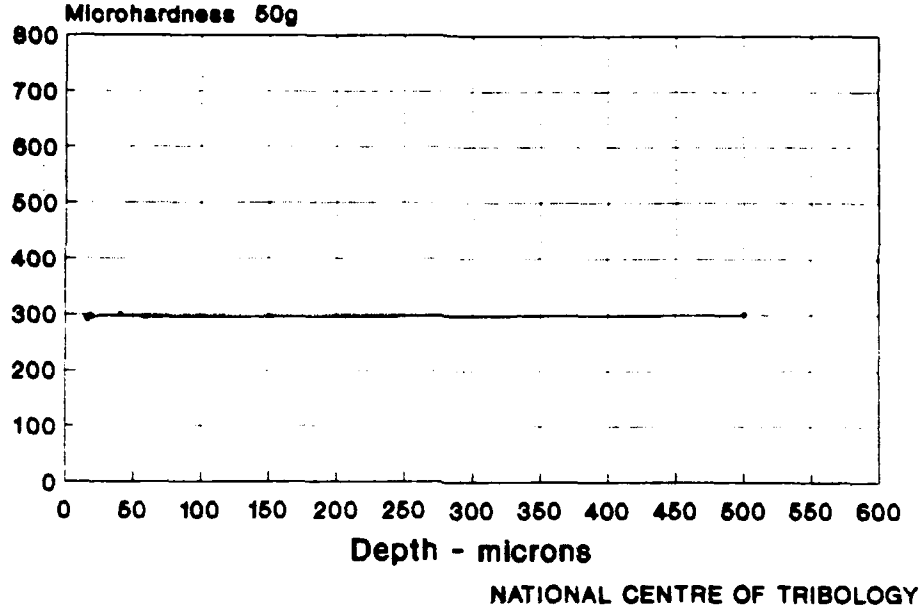
NATIONAL CENTRE OF TRIBOLOGY

MICROHARDNESS DEPTH PROFILE
HSSA37/ DELTA NITROCARBURIZED +TiN (SIP)

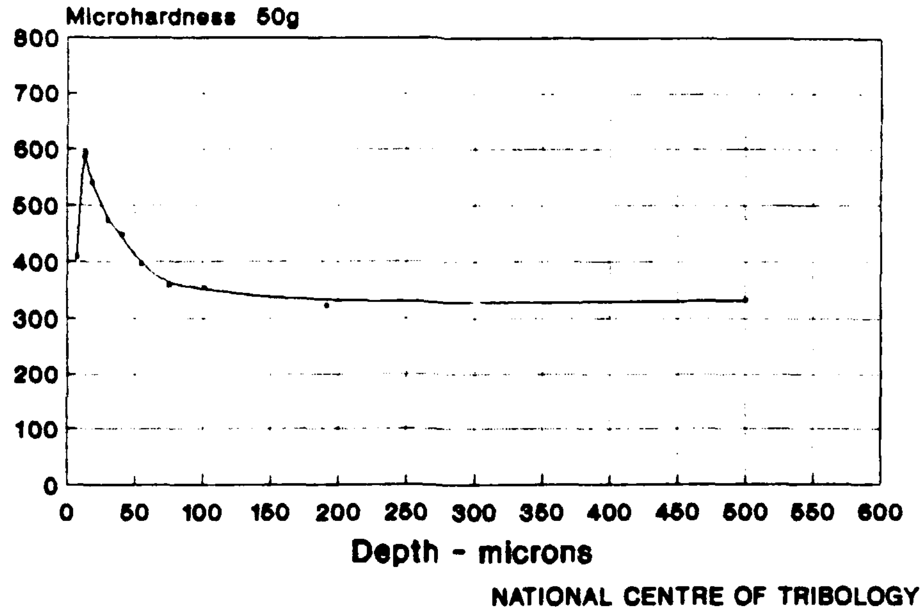


NATIONAL CENTRE OF TRIBOLOGY

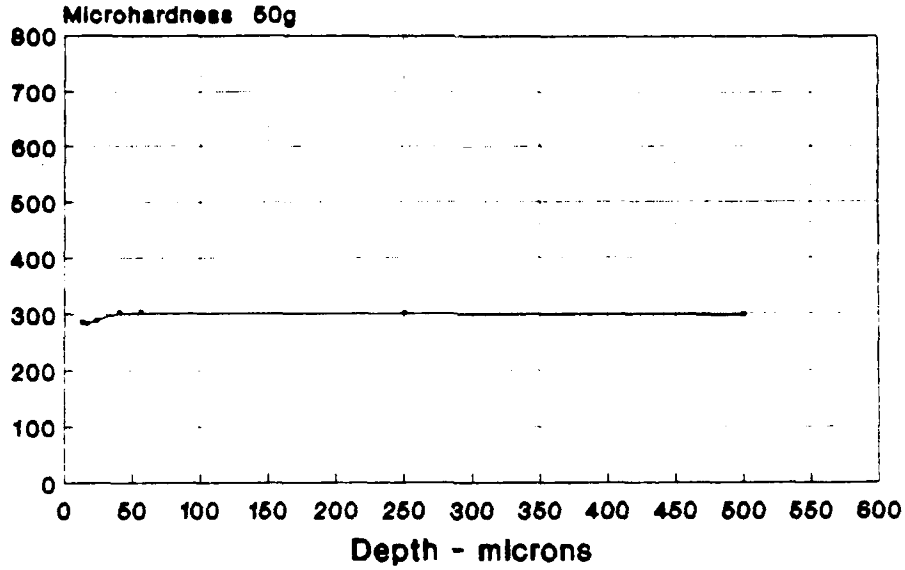
MICROHARDNESS DEPTH PROFILE
HSSA38/ DELTA NITROCARBURIZED + TiN (AE)



MICROHARDNESS DEPTH PROFILE
HSSA39 / HSSA30 HEAT TREATED

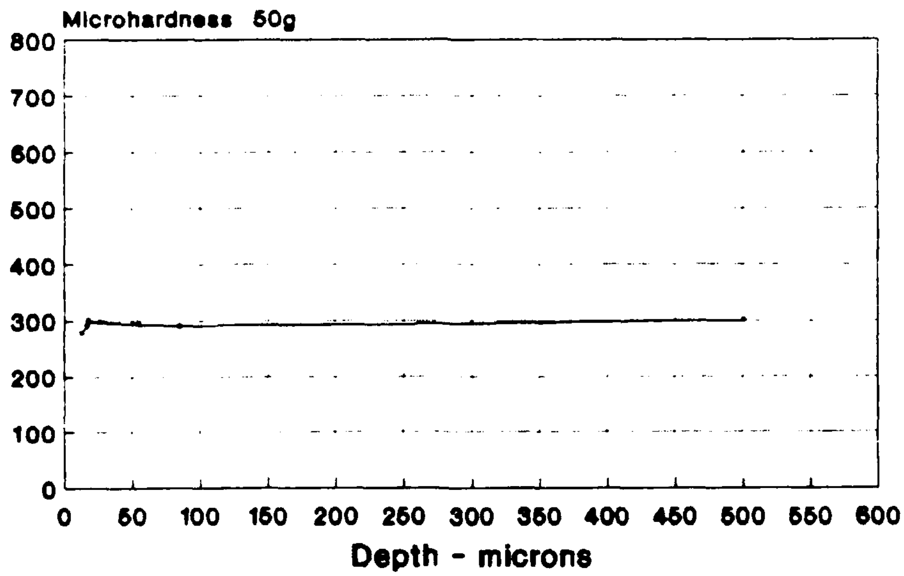


MICROHARDNESS DEPTH PROFILE
HSSA40/ HSSA31 HEAT TREATED



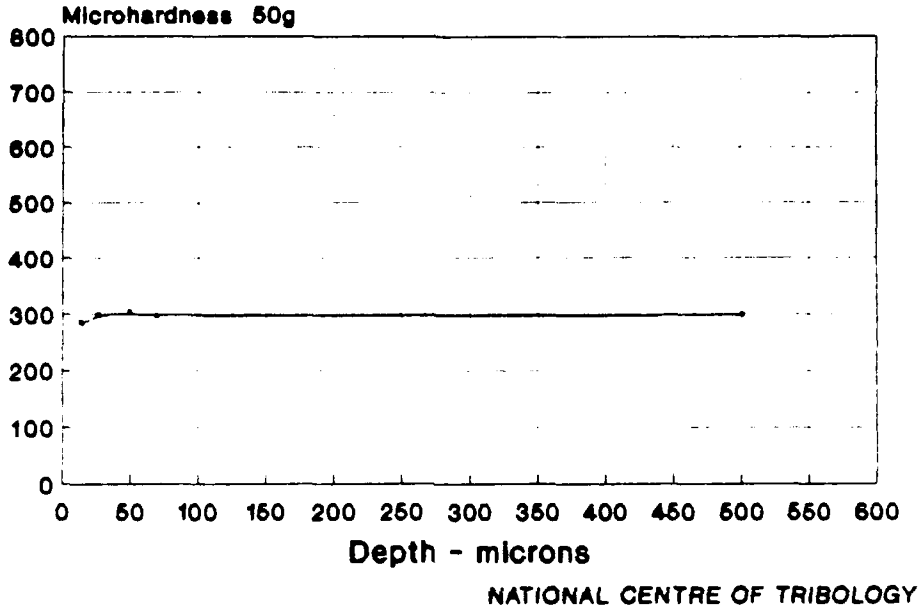
NATIONAL CENTRE OF TRIBOLOGY

MICROHARDNESS DEPTH PROFILE
HSSA41/ DELTA NITROCARBURIZED (2 HOURS)3

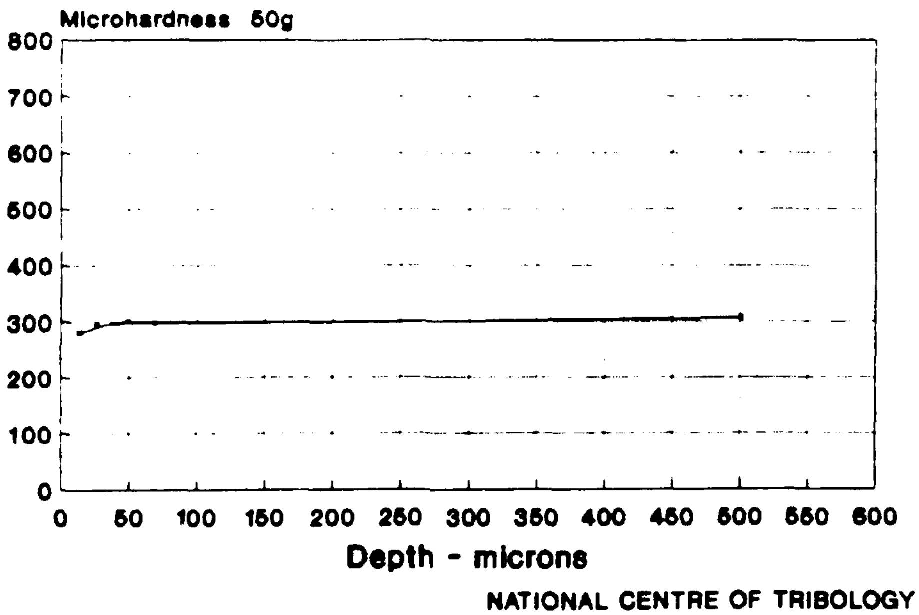


NATIONAL CENTRE OF TRIBOLOGY

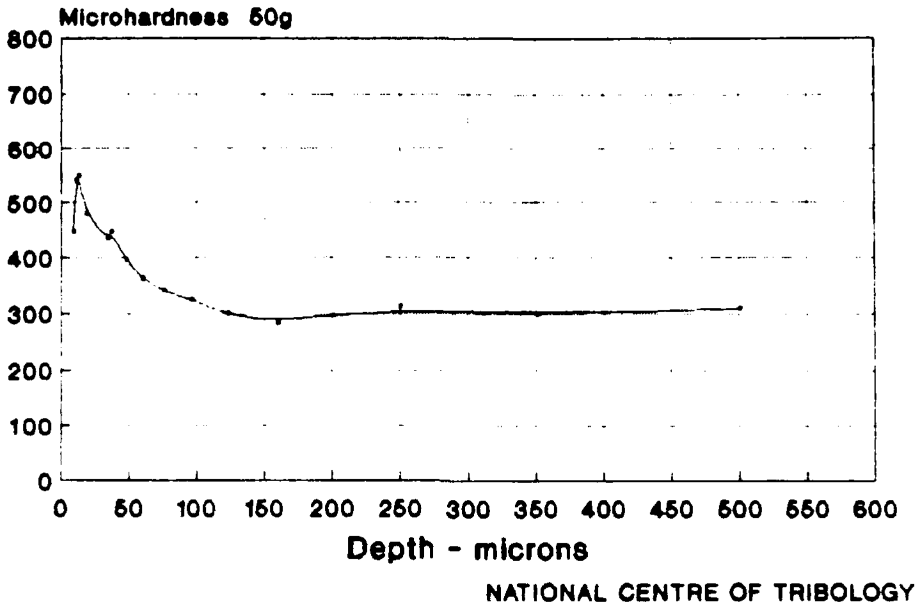
MICROHARDNESS DEPTH PROFILE
HSSA42/ DELTA NITROCARBURIZED (4 HOURS)4



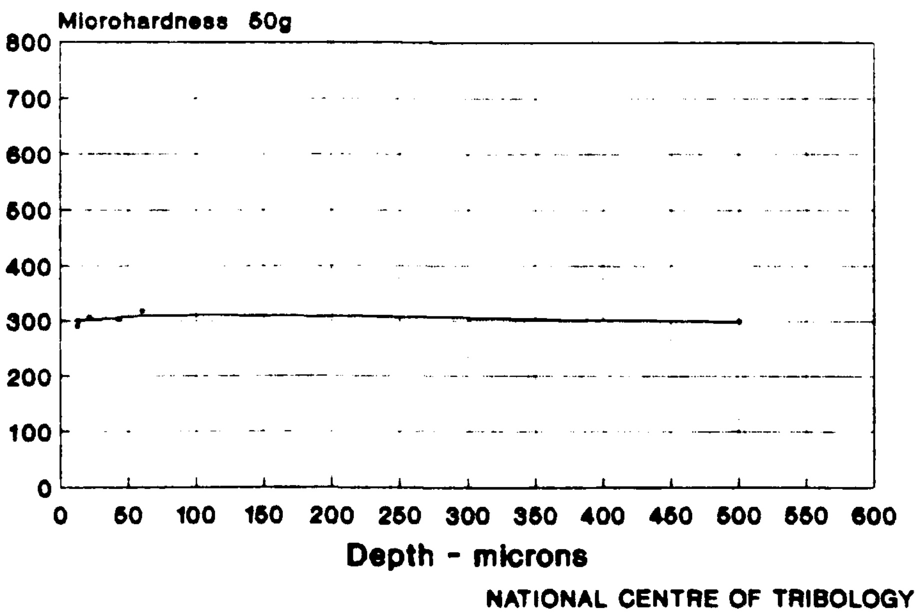
MICROHARDNESS DEPTH PROFILE
HSSA43/ DELTA NITROCARBURIZED (6 HOURS)5



MICROHARDNESS DEPTH PROFILE
HSSA45/ BETA NITROCARBURIZED 3

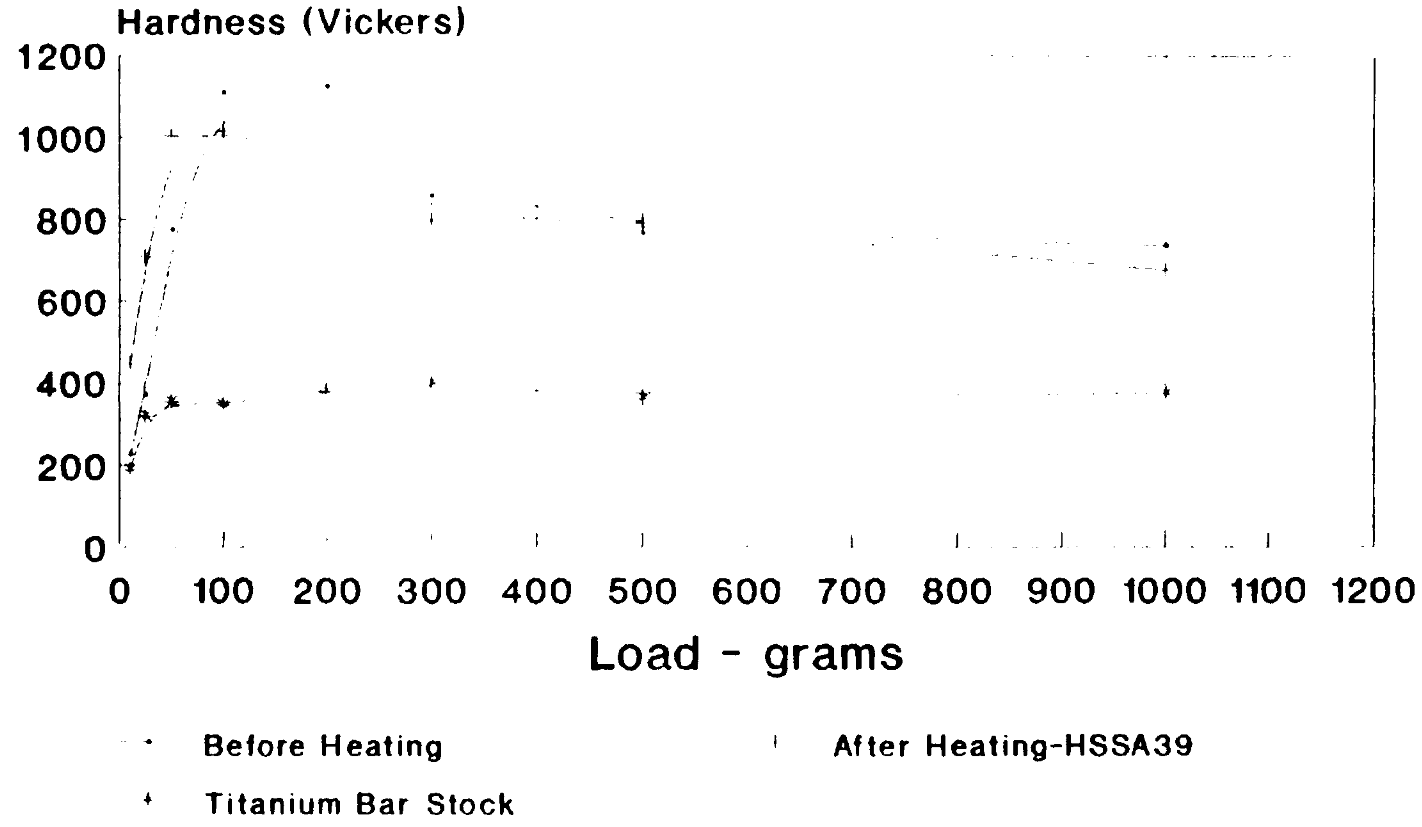


MICROHARDNESS DEPTH PROFILE
HSSA46/ DELTA NITROCARBURIZED 6



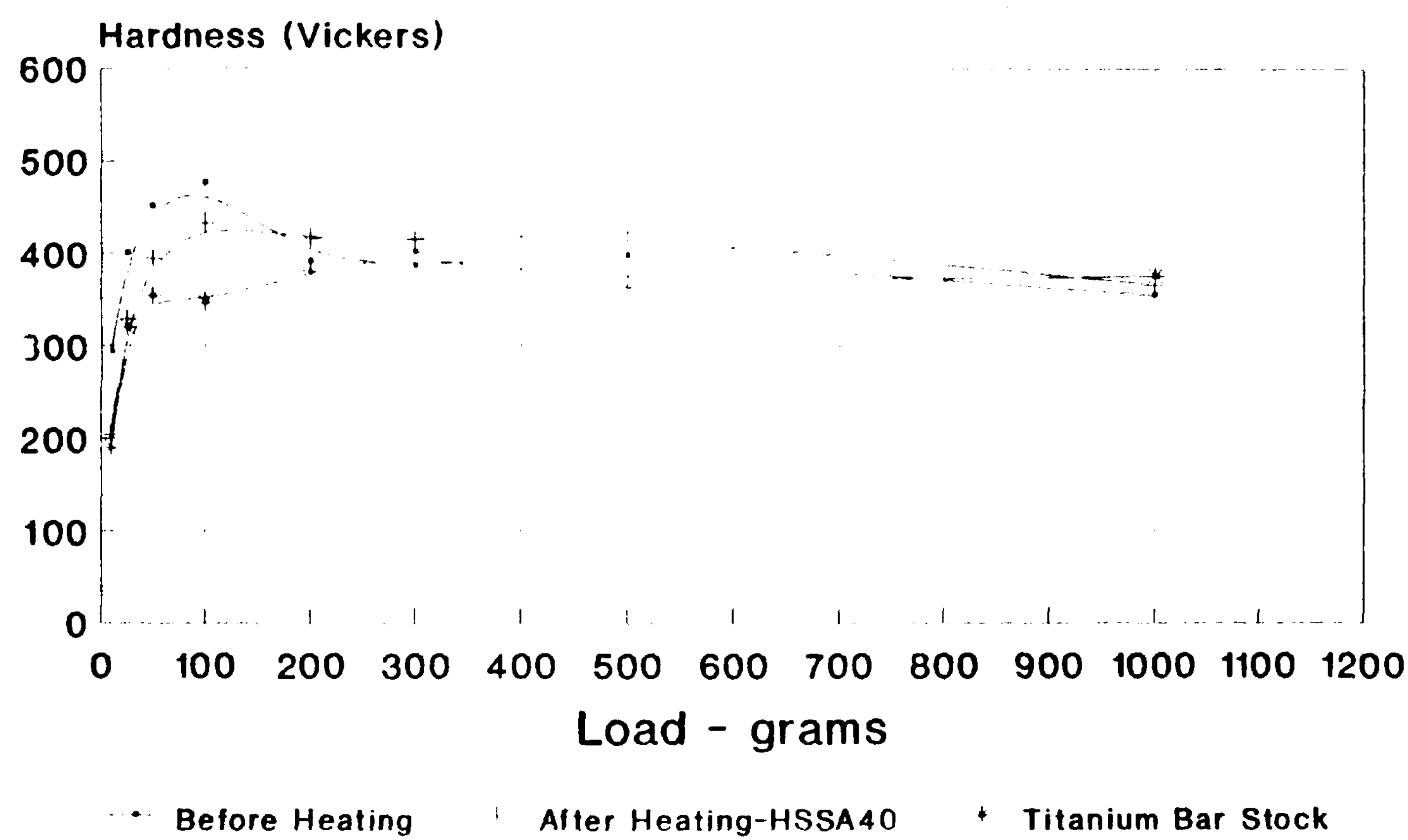
APPENDIX 4. Surface Hardness Measurements

MICROHARDNESS SURFACE PROFILE
HSSA 30/ BETA NITROCARBURIZED #2



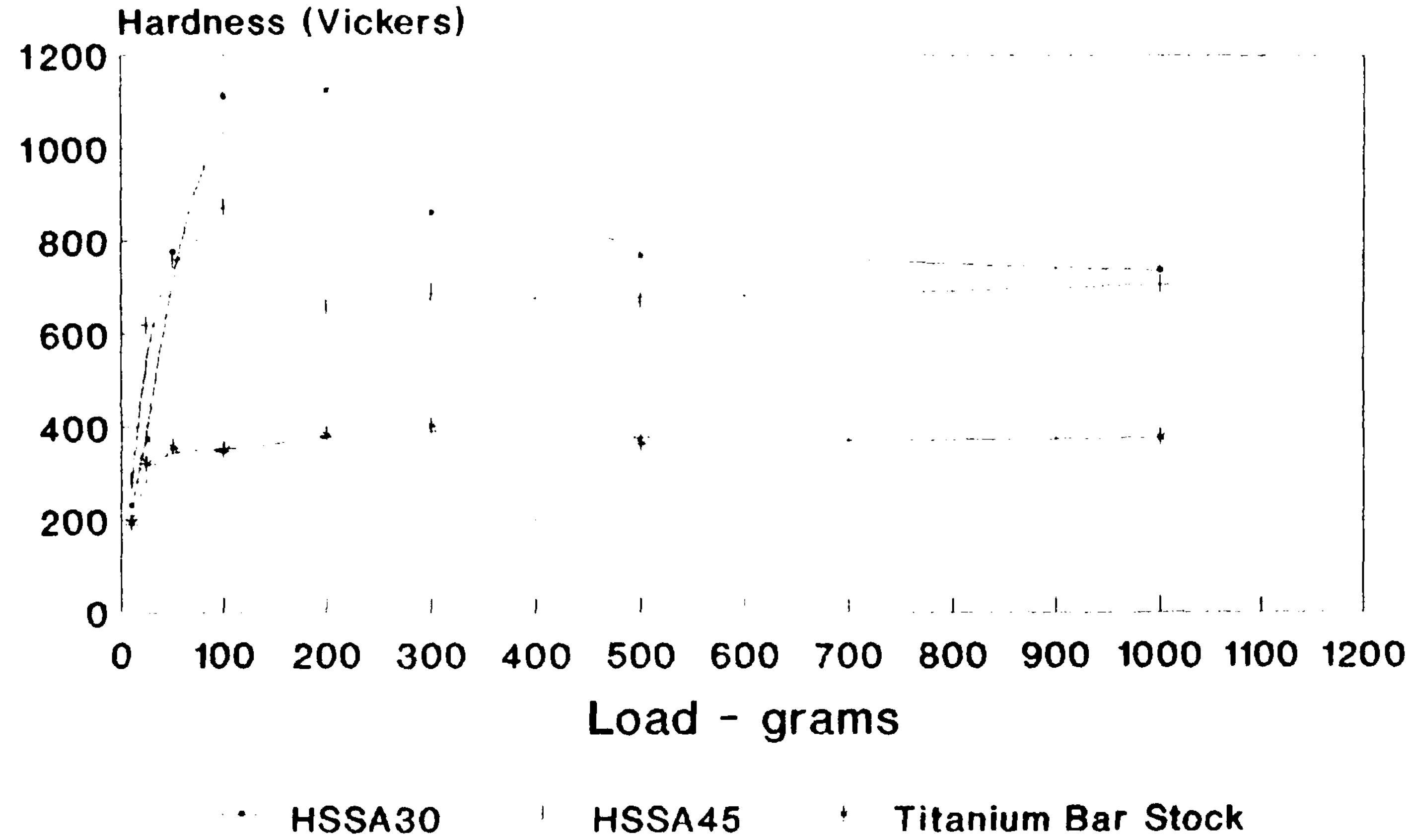
NATIONAL CENTRE OF TRIBOLOGY

MICROHARDNESS SURFACE PROFILE
HSSA 31/ DELTA NITROCARBURIZED #2



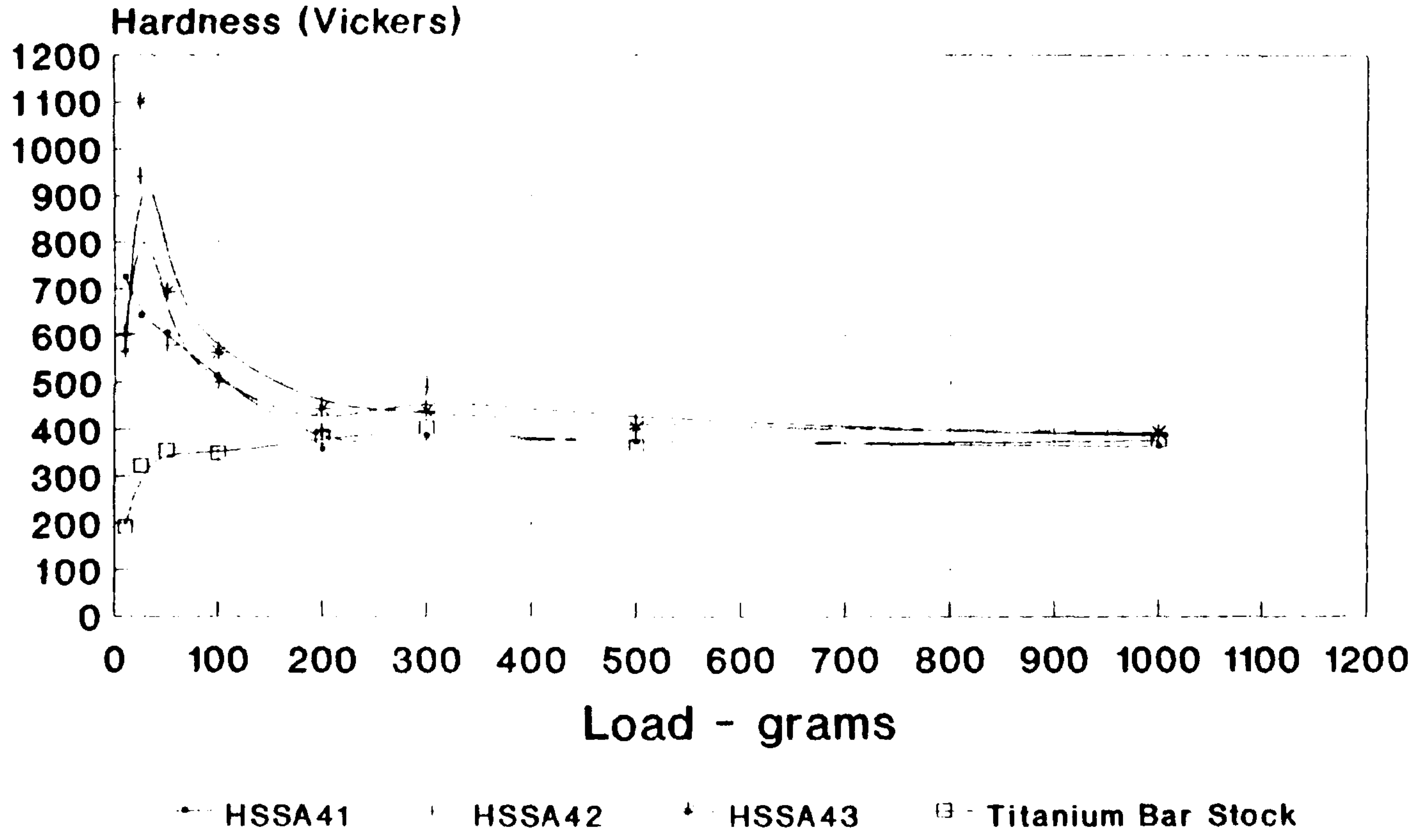
NATIONAL CENTRE OF TRIBOLOGY

MICROHARDNESS SURFACE PROFILE
BETA NITROCARBURIZED



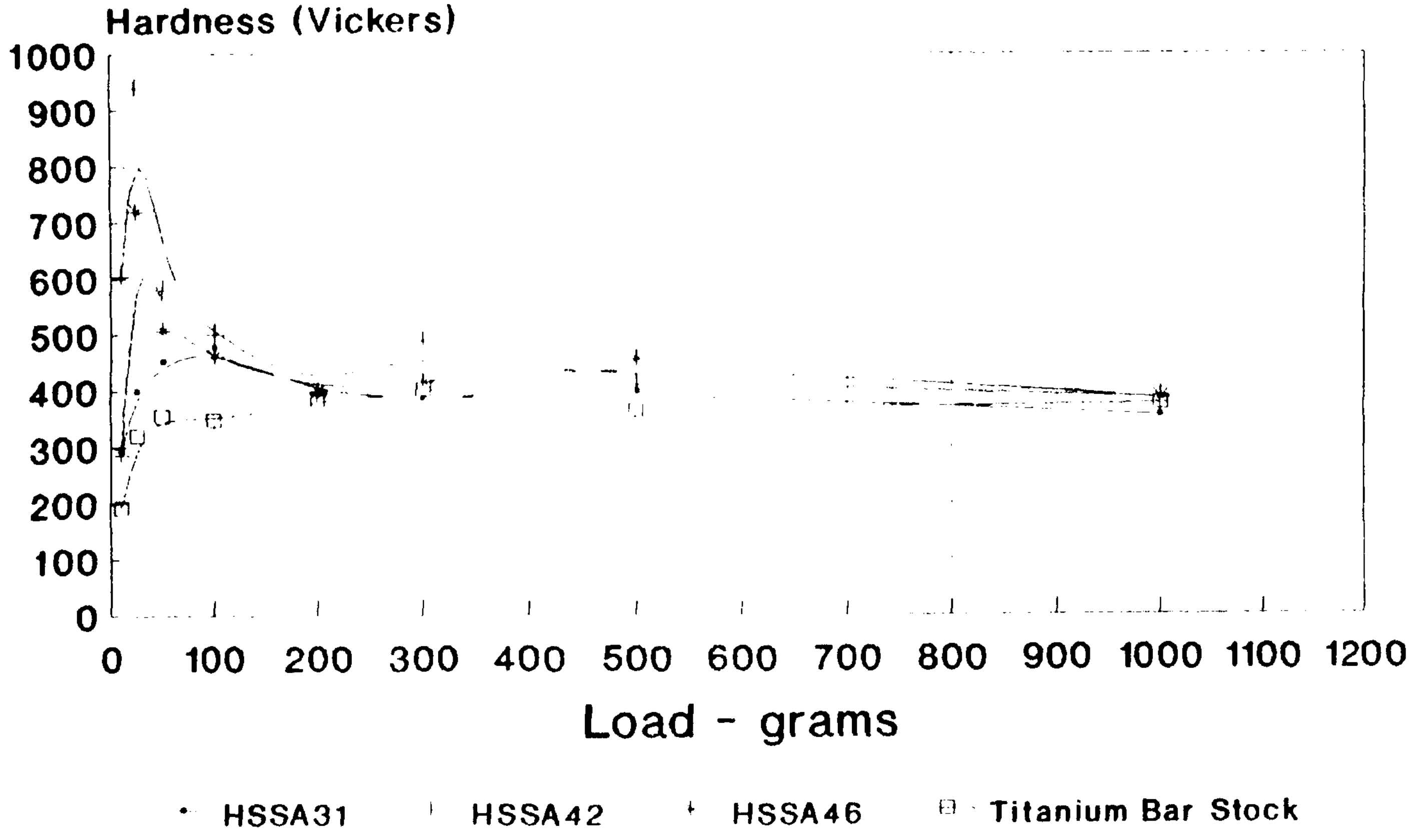
NATIONAL CENTRE OF TRIBOLOGY

MICROHARDNESS SURFACE PROFILE
DELTA NITROCARBURIZED



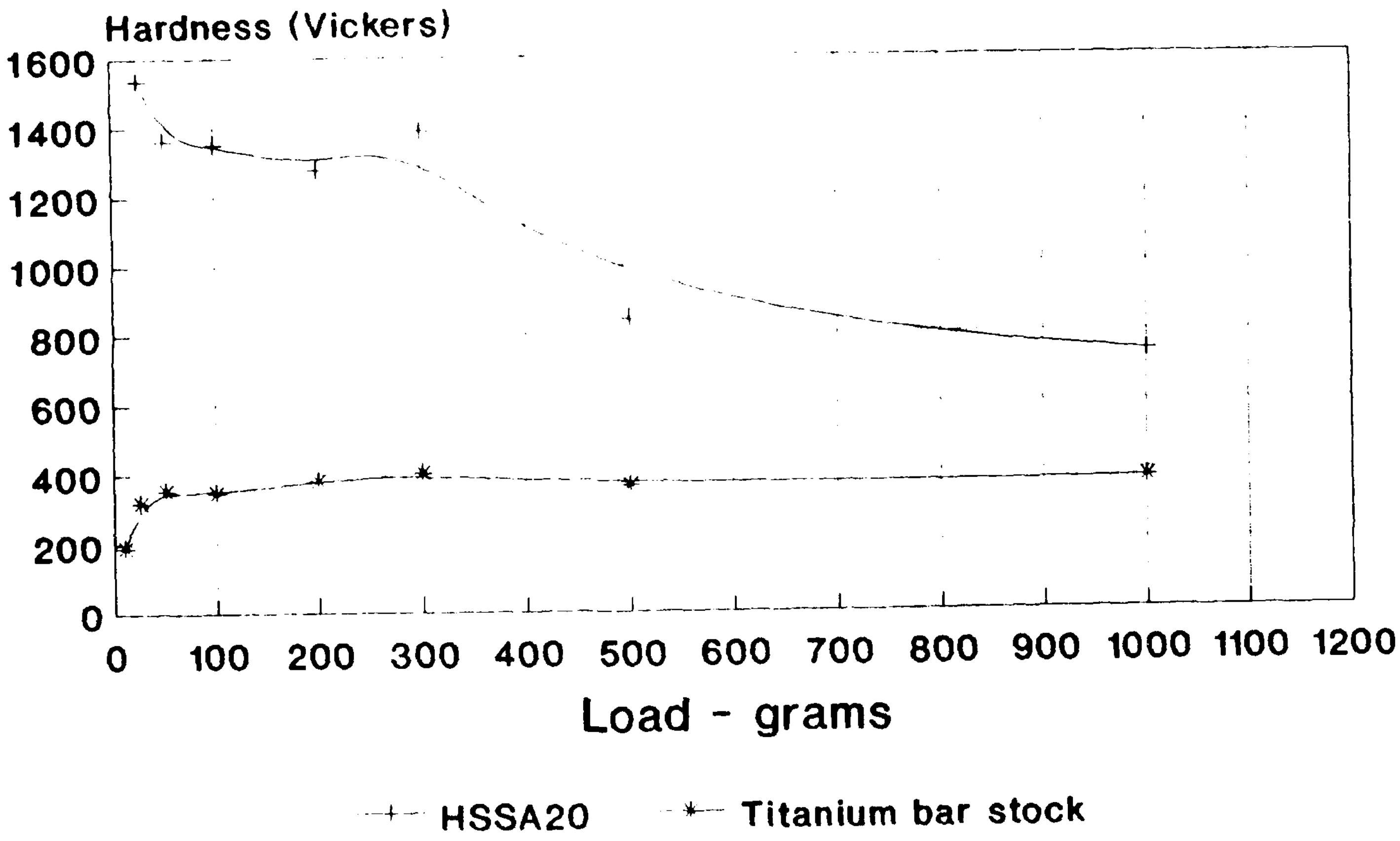
NATIONAL CENTRE OF TRIBOLOGY

MICROHARDNESS SURFACE PROFILE
DELTA NITROCARBURIZED



NATIONAL CENTRE OF TRIBOLOGY

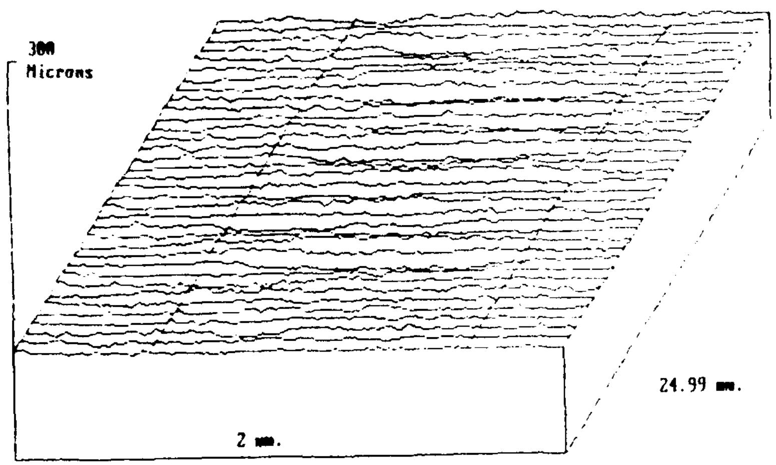
MICROHARDNESS SURFACE PROFILE
CARBONITRIDED



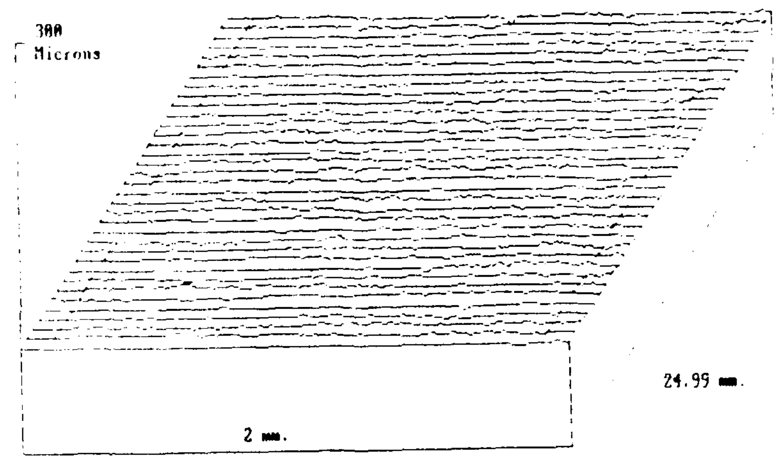
NATIONAL CENTRE OF TRIBOLOGY

APPENDIX 5: 20N Wear Profiles of Wear Tracks In Air

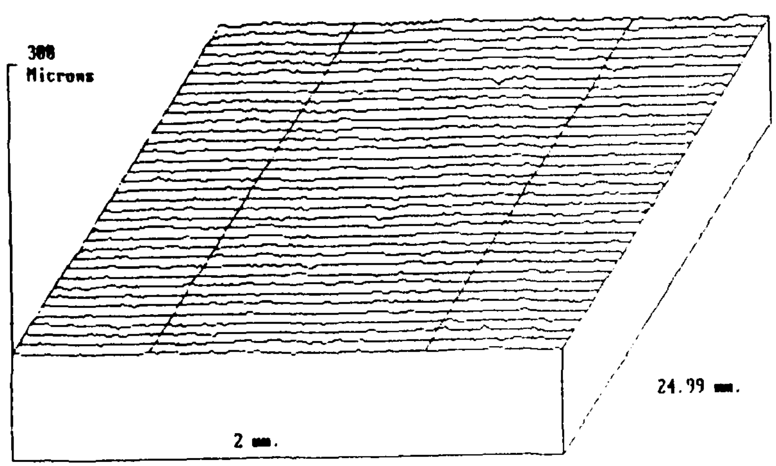
HSSA26 HT plasma nitriding
Wear Volume 0.00 mm^3



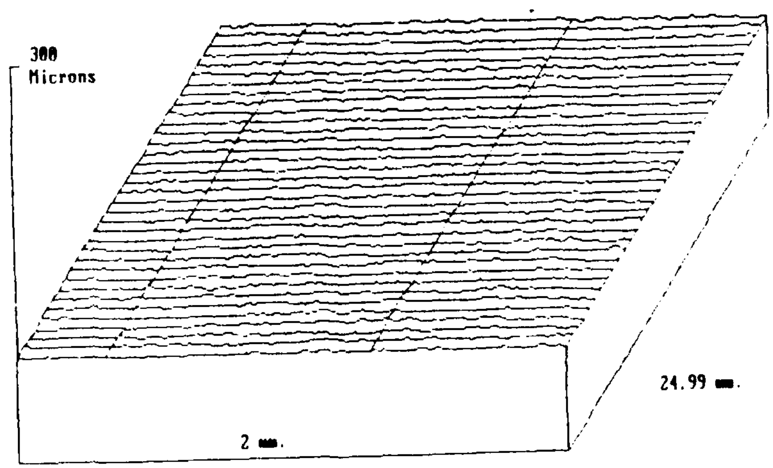
HSSA30 Beta nitrocarburized 2
Wear Volume 0.00 mm^3



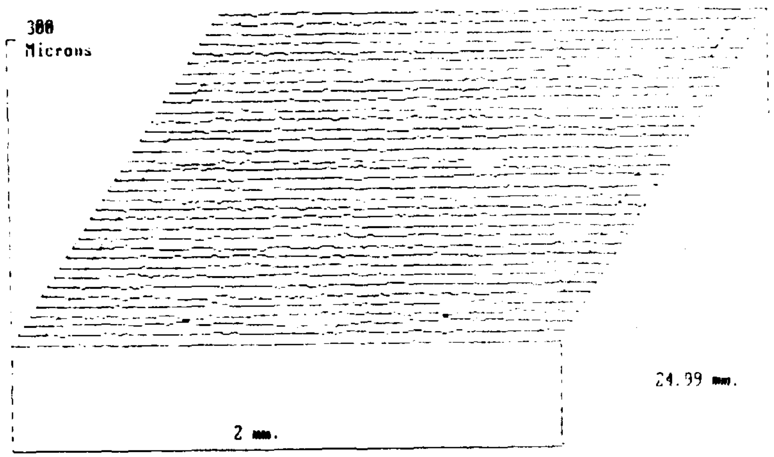
HSSA28 Lucas Nitrotec
Wear Volume 0.00 mm^3



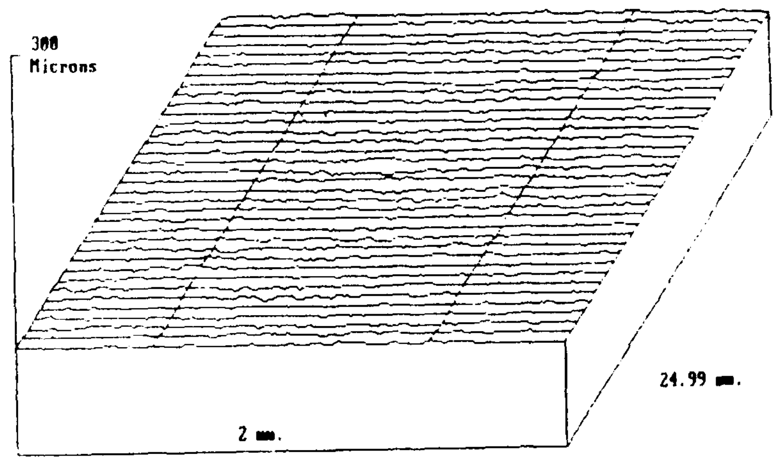
HSSA31 Delta nitrocarburized 2
Wear Volume 0.00 mm^3



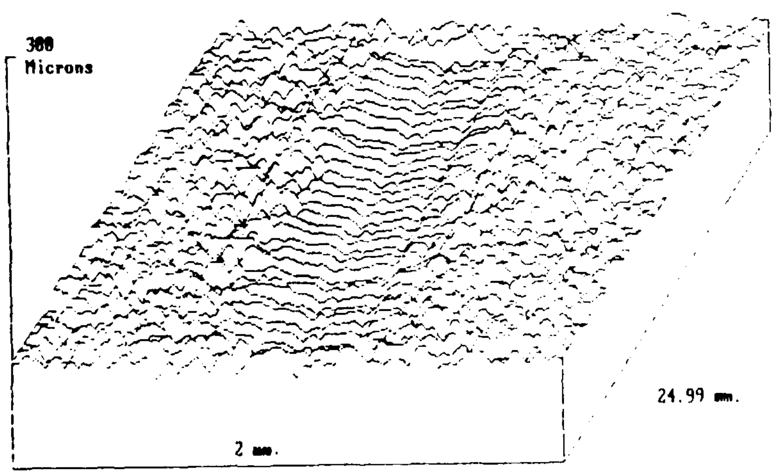
HSSA32 Carbonitrided 2
Wear Volume 0.00 mm^3



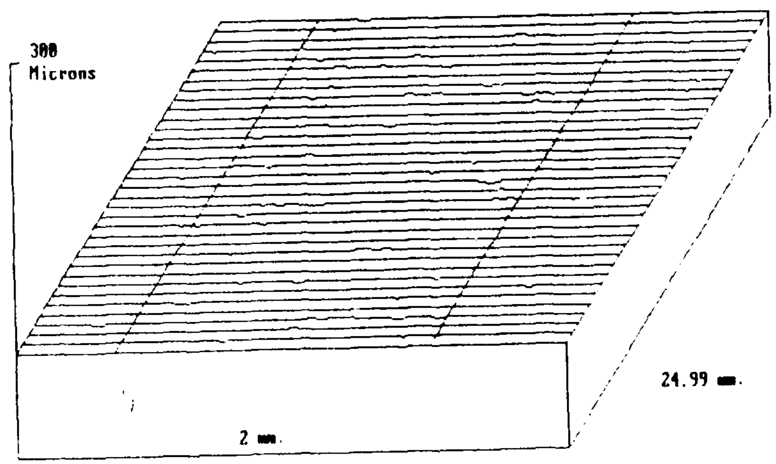
HSSA34 Carbonitrided 3
Wear Volume 9.28×10^{-3} mm^3



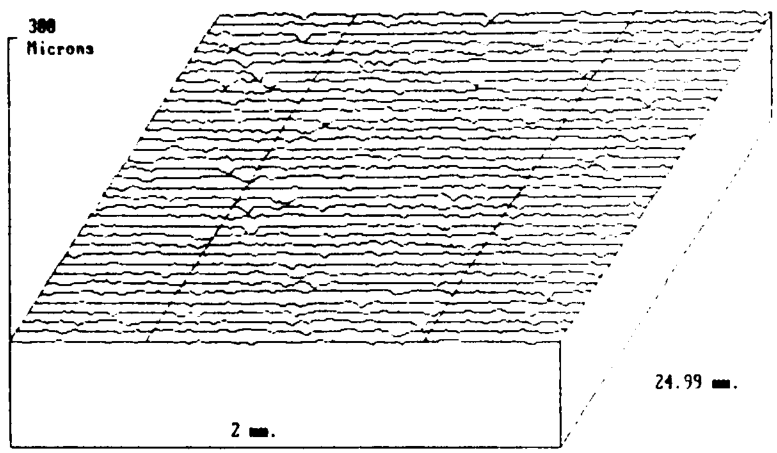
HSSA33 Pack Aluminised 4
Wear Volume 0.11 mm^3



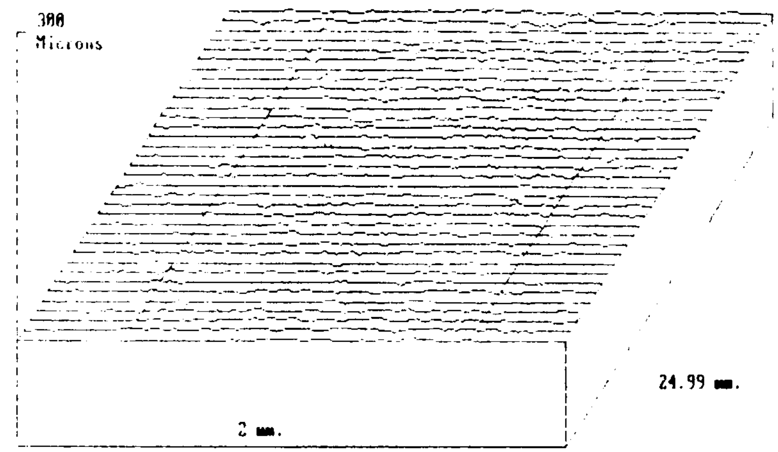
HSSA35 B Nitrocarburized + TiN (SIP)
Wear Volume 2.55×10^{-4} mm^3



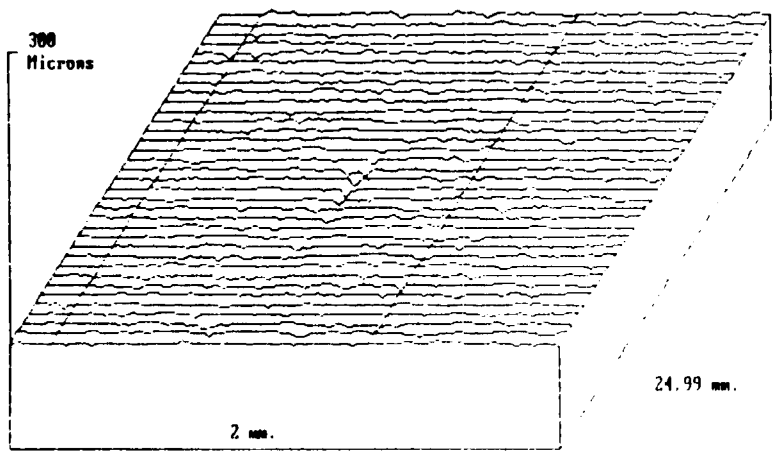
HSSA36 D Nitrocarburized + TiN (SIP) 1
Wear Volume 0.00 mm^3



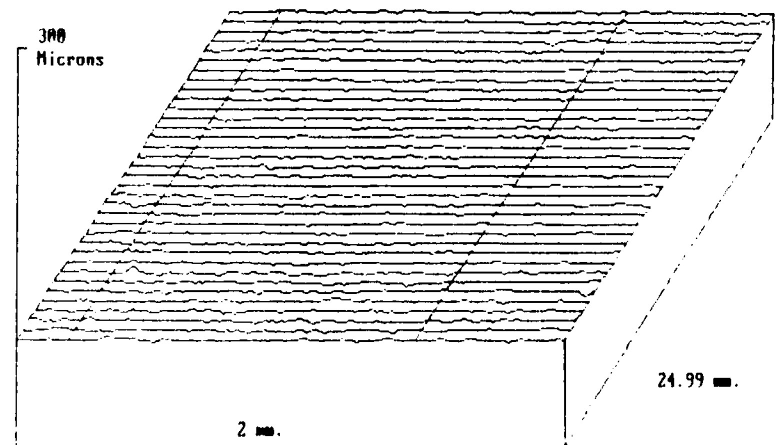
HSSA38 D Nitrocarburized + TiN (Arc)
Wear Volume 0.00 mm^3



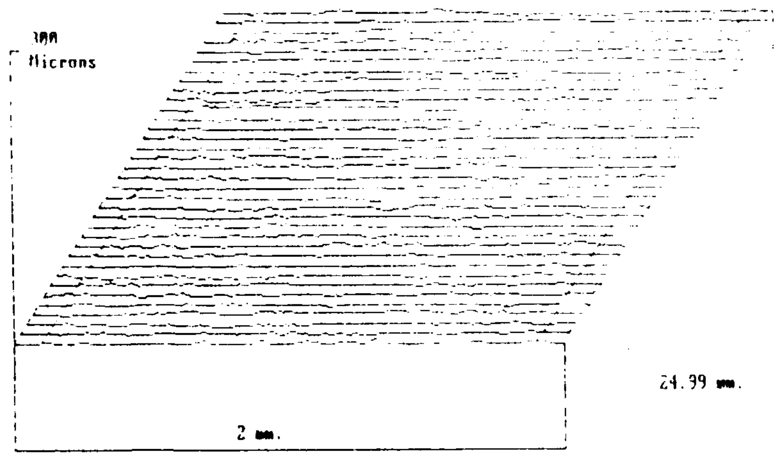
HSSA37 B Nitrocarburized + TiN (Arc)
Wear Volume 4.19×10^{-4} mm^3



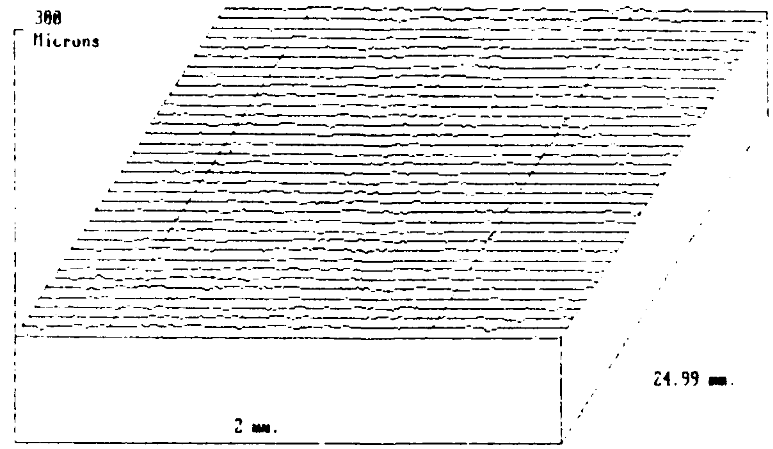
HSSA39 HSSA30 Heat Treated
Wear Volume 1.04×10^{-2} mm^3



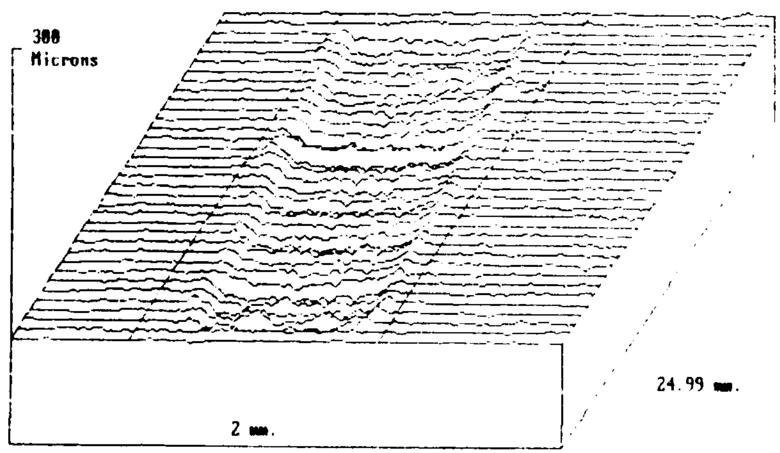
HSSA40 HSSA31 Heat Treated
Wear Volume 0.00 mm³



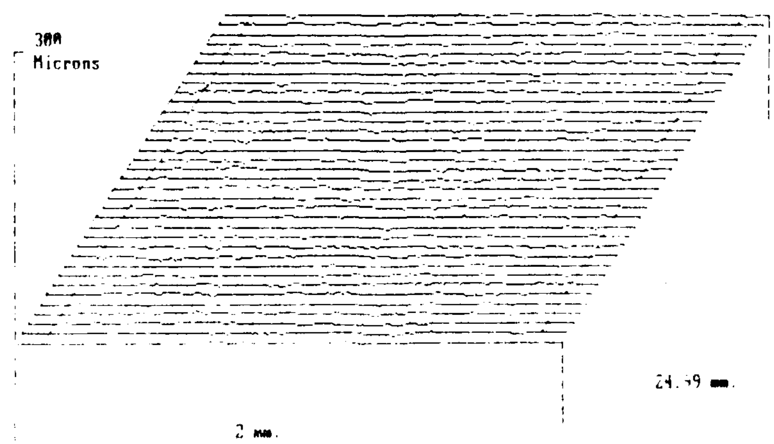
HSSA42 Delta Nitrocarburized (4hrs) 4
Wear Volume 0.00 mm³



HSSA41 Delta Nitroca burized (2hrs) 3
Wear Volume 0.11 mm³

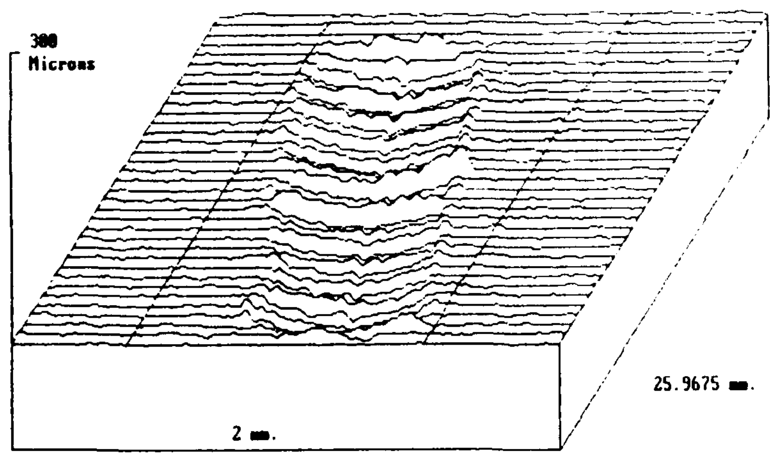


HSSA43 Delta Nitrocarburized (6hrs) 5
Wear Volume 3.63×10^{-3} mm³



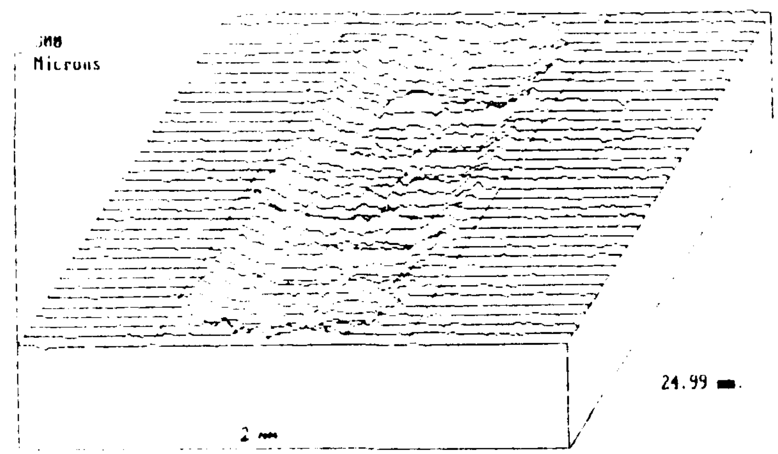
HSSA44 Plain Titanium

Wear Volume 0.10 mm³



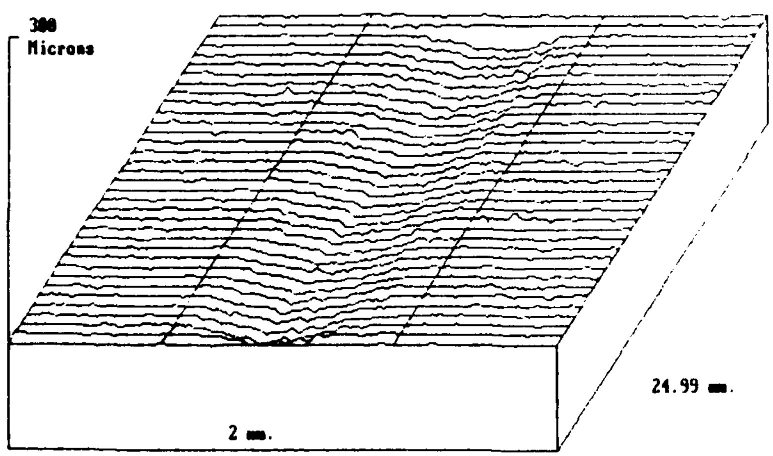
HSSA46 Delta Nitrocarburized 6

Wear Volume 0.14 mm³



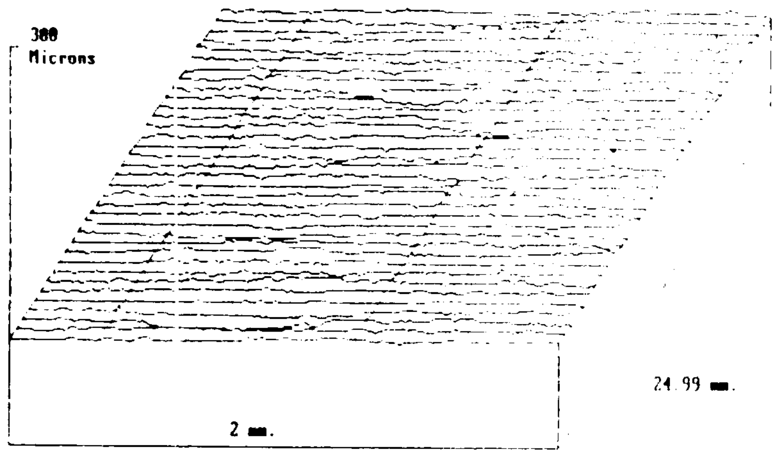
HSSA45 Beta Nitrocarburized 3

Wear Volume 9.46×10^{-2} mm³

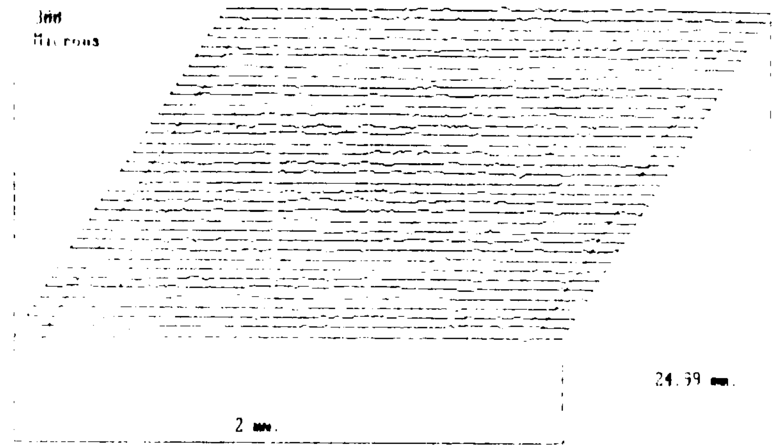


APPENDIX 6: 50N Wear Profiles of Wear Tracks In Air

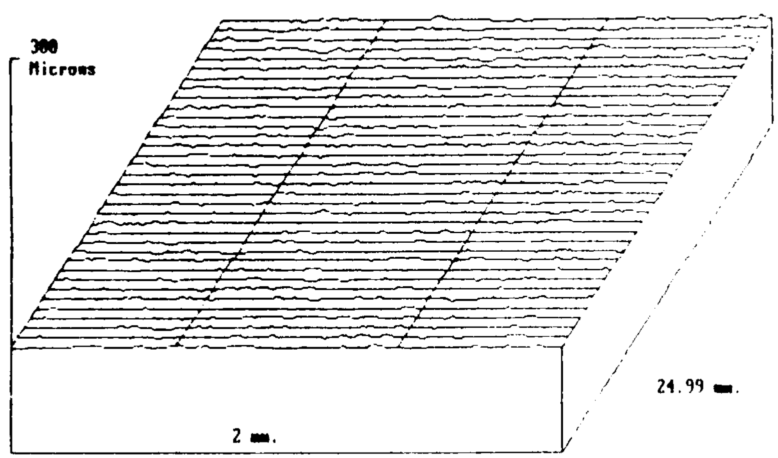
HSSA26 HT plasma nitriding
Wear Volume 0.00 mm^3



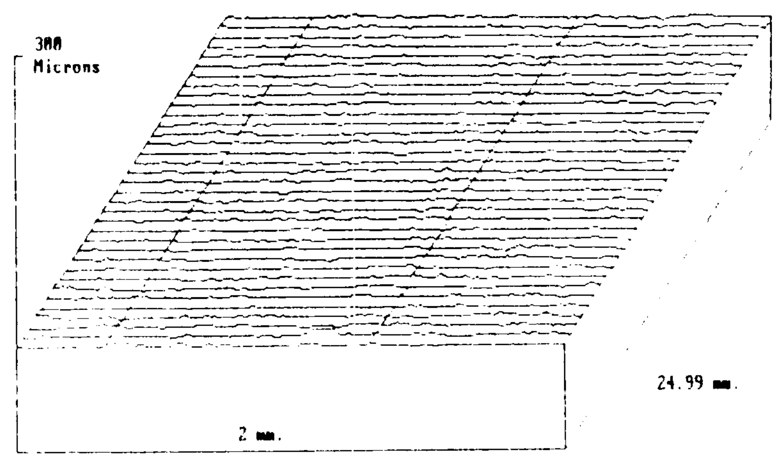
HSSA30 Beta nitrocarburized 2
Wear Volume 0.00 mm^3



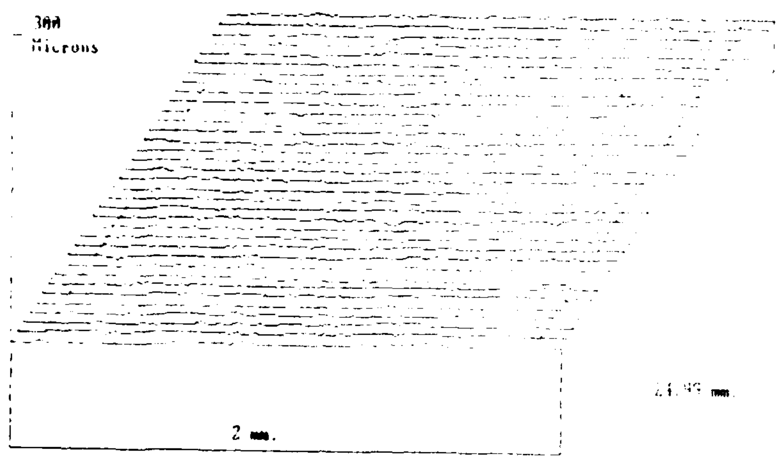
HSSA28 Lucas Nitrotec
Wear Volume 0.00 mm^3



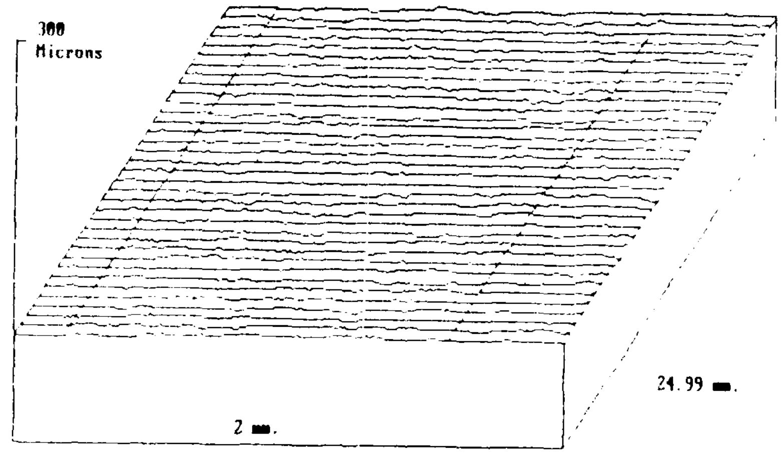
HSSA31 Delta nitrocarburized 2
Wear Volume 0.00 mm^3



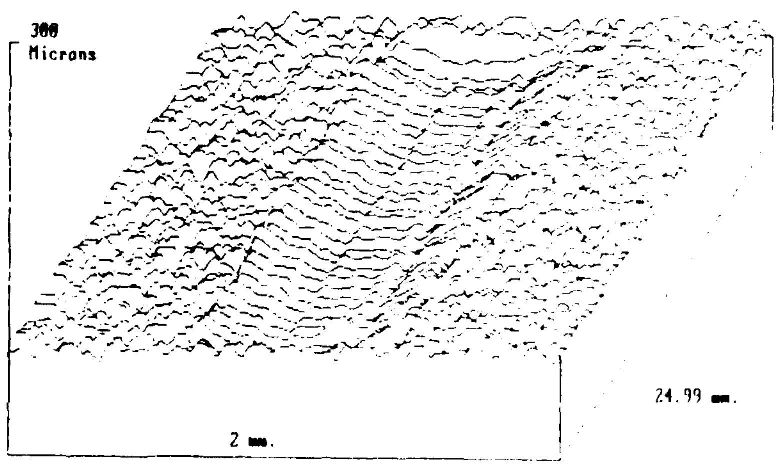
HSSA32 Carbonitrided 2
Wear Volume 1.10×10^{-3} mm³



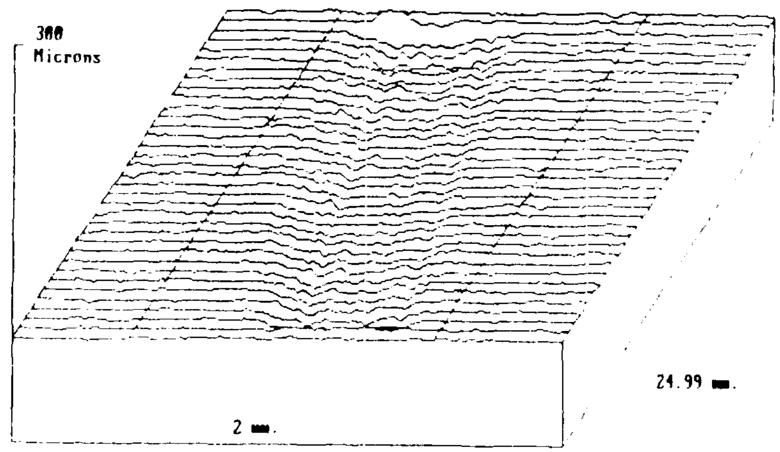
HSSA34 Carbonitrided 3
Wear Volume 2.26×10^{-3} mm³



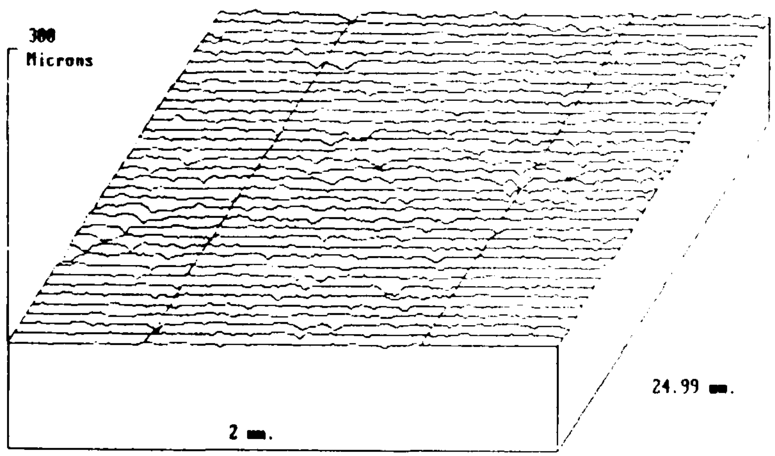
HSSA33 Pack Aluminised 4
Wear Volume 0.18 mm³



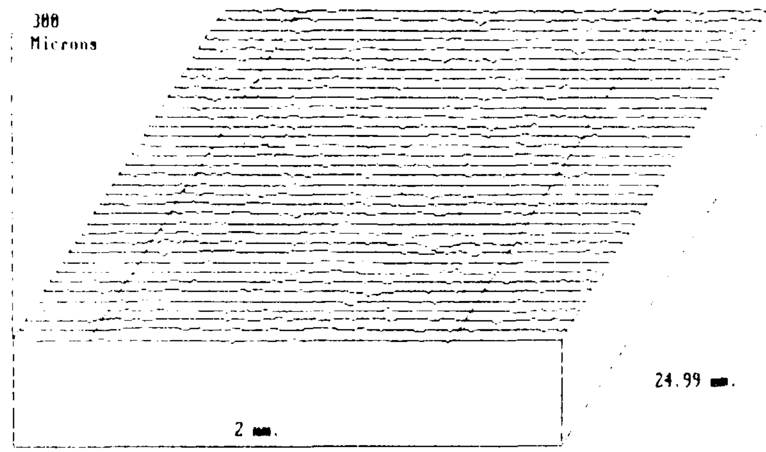
HSSA35 B Nitrocarburized + TiN (SIP)
Wear Volume 0.08 mm³



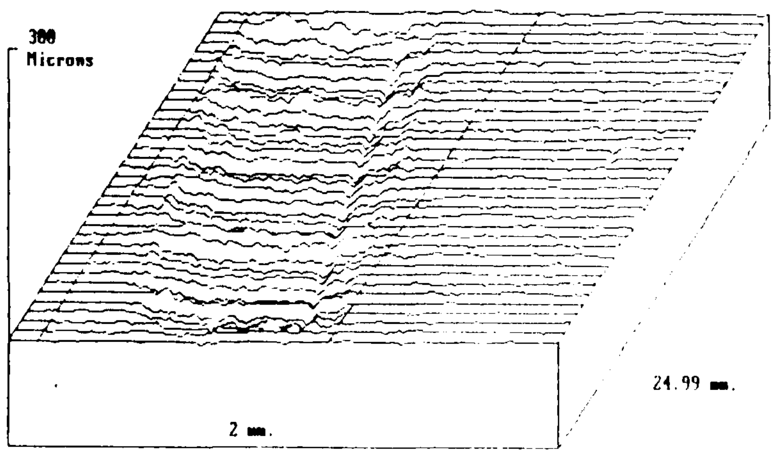
HSSA36 D Nitrocarburized + TiN (SIP) 1
Wear Volume 1.84×10^{-3} mm^3



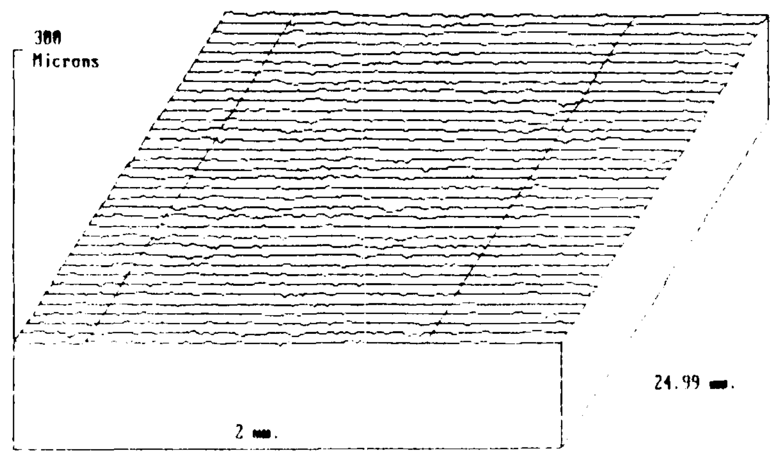
HSSA38 D Nitrocarburized + TiN (Arc)
Wear Volume 0.00 mm^3



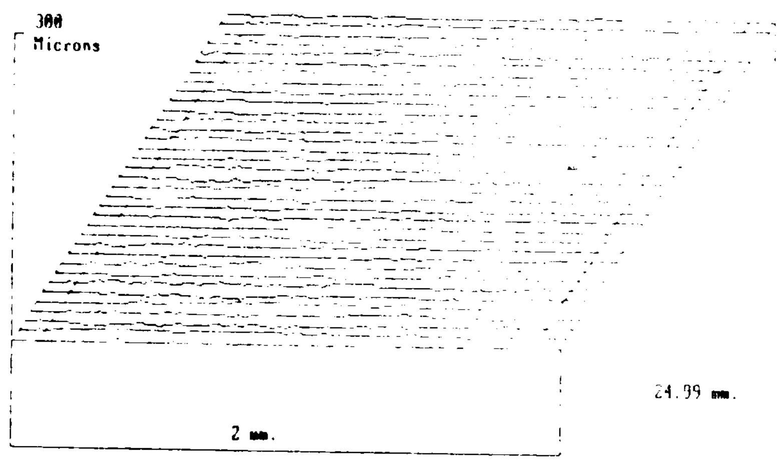
HSSA37 B Nitrocarburized + TiN (Arc)
Wear Volume 0.16 mm^3



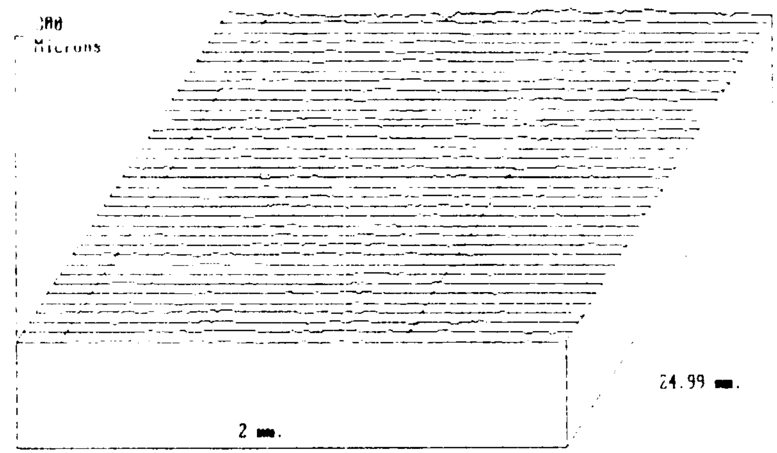
HSSA39 HSSA30 Heat Treated
Wear Volume 9.20×10^{-3} mm^3



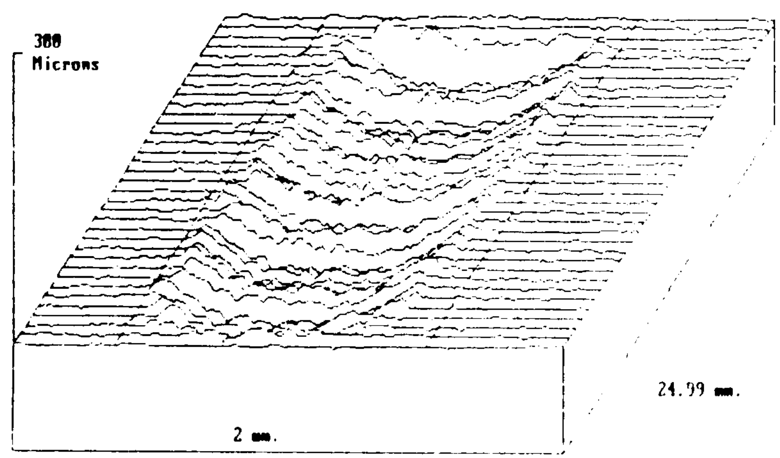
HSSA40 HSSA31 Heat Treated
Wear Volume 0.00 mm^3



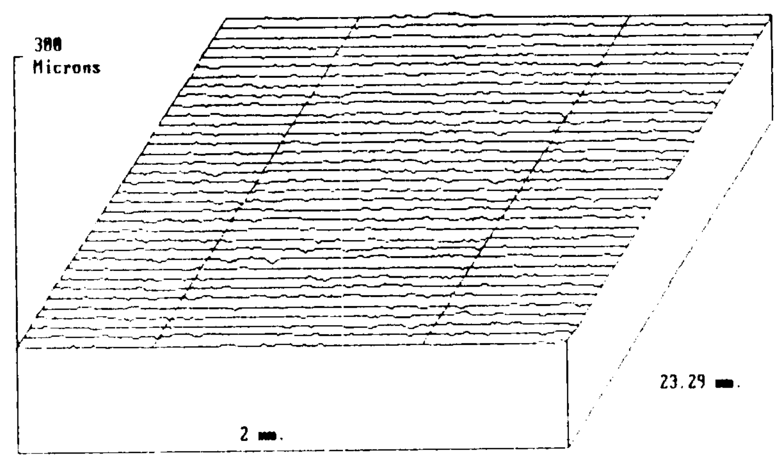
HSSA42 Delta Nitrocarburized (4hrs) 4
Wear Volume 0.00 mm^3



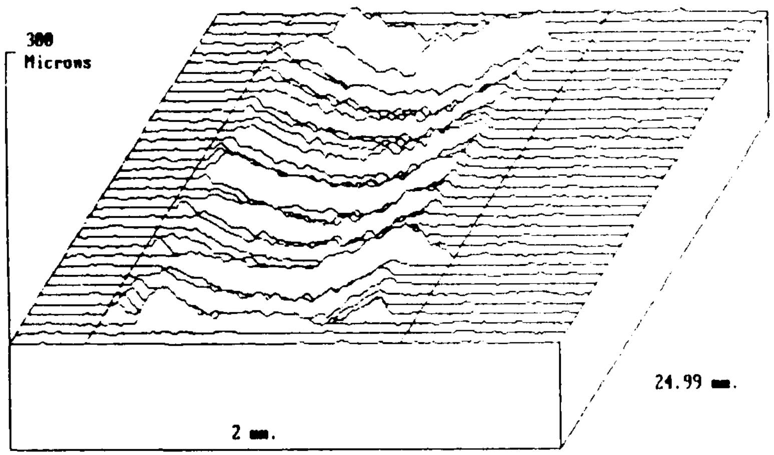
HSSA41 Delta Nitrocarburized (2hrs) 3
Wear Volume 0.29 mm^3



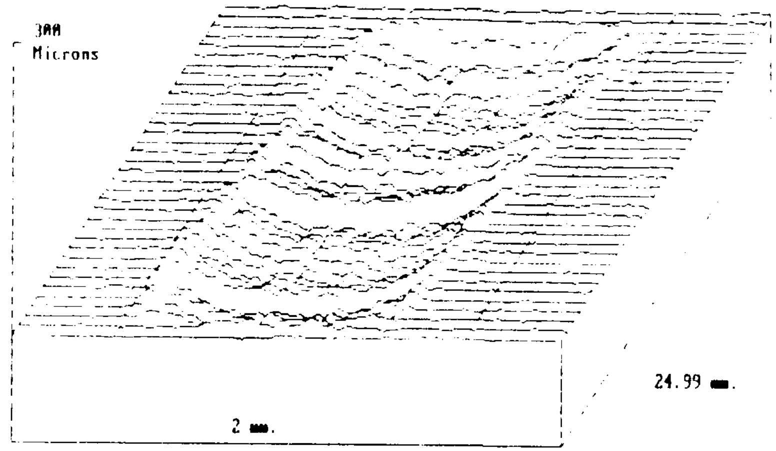
HSSA43 Delta Nitrocarburized (6hrs) 5
Wear Volume 0.00 mm^3



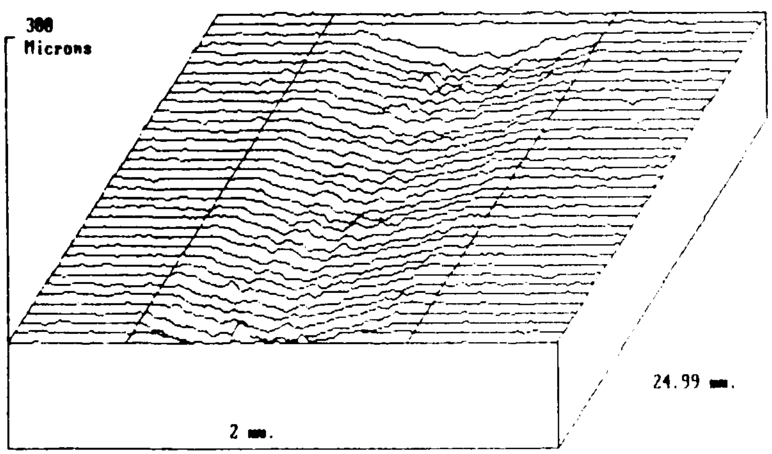
HSSA44 Plain Titanium
Wear Volume 0.24 mm³



HSSA46 Delta Nitrocarburized 6
Wear Volume 0.30 mm³

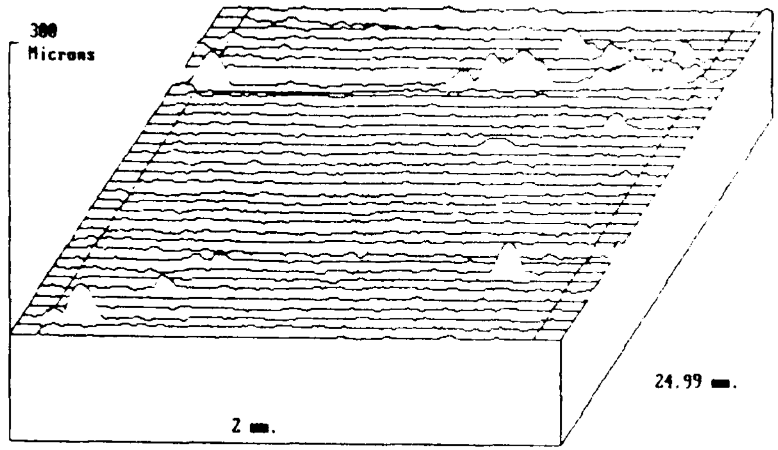


HSSA45 Beta Nitrocarburized 3
Wear Volume 0.20 mm³

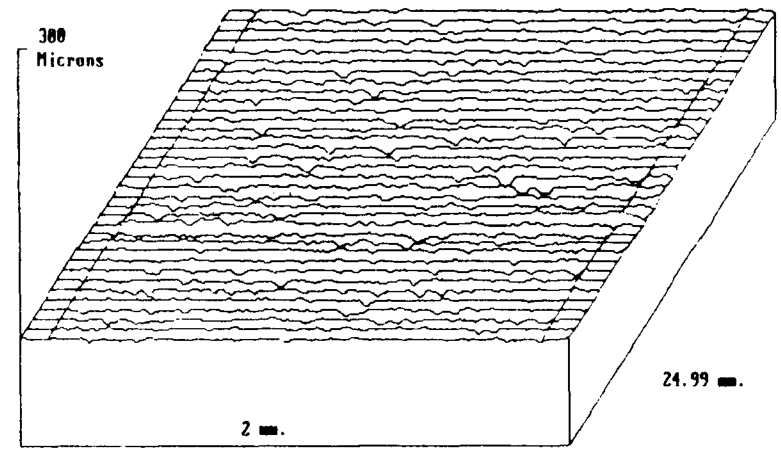


APPENDIX 7: 20N Wear Profiles of Wear Tracks in Nitrogen

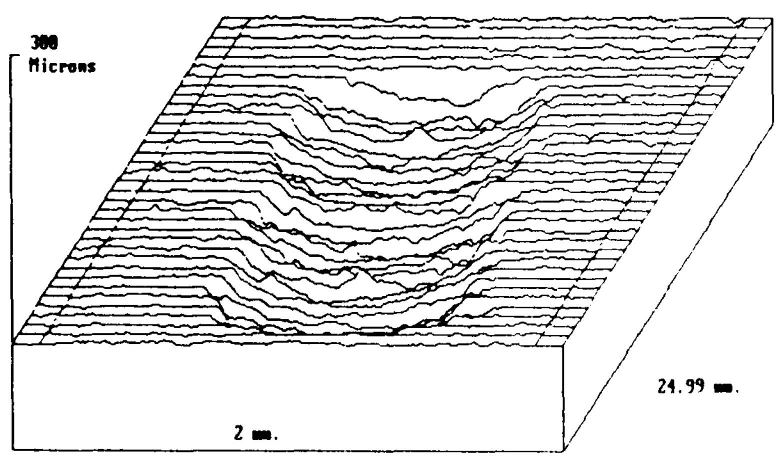
HSSA30 Beta nitrocarburized 2
Wear Volume 2.13×10^{-2} mm^3



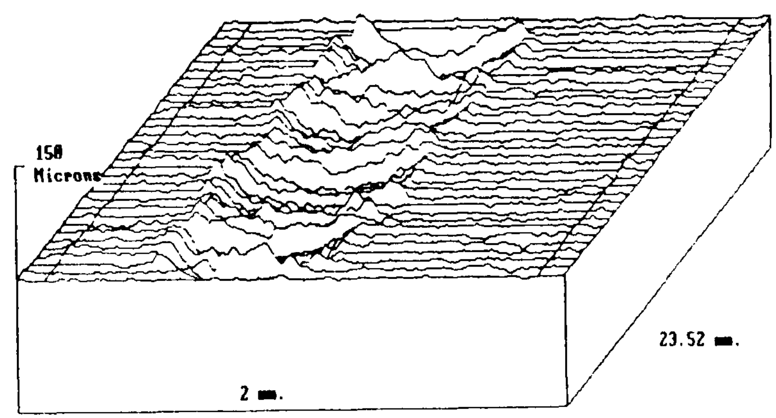
HSSA36 D Nitrocarburized + TiN (SIP) 1
Wear Volume 1.59×10^{-2} mm^3



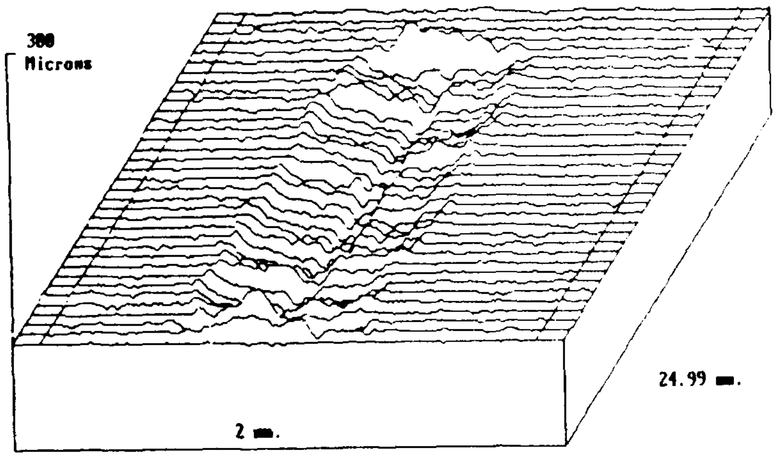
HSSA34 Carbonitrided 3
Wear Volume 0.38 mm^3



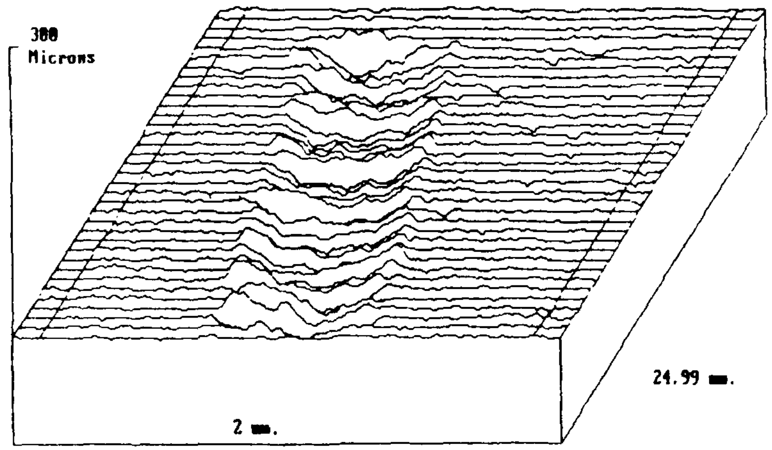
HSSA41 Delta Nitrocarburized (2hrs) 3
Wear Volume 0.11 mm^3



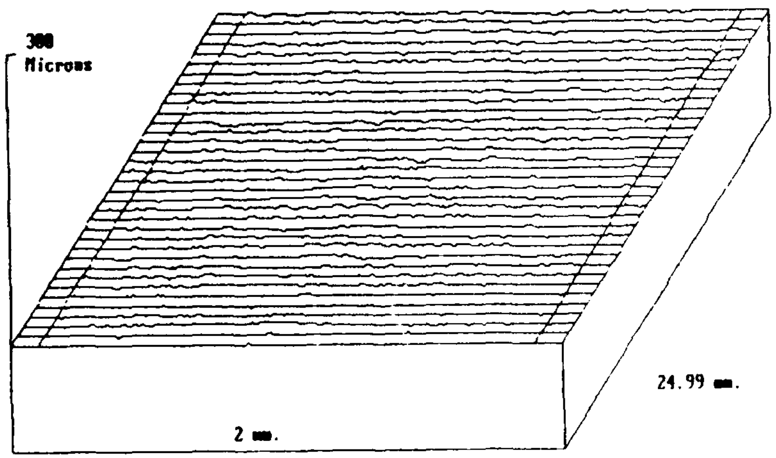
HSSA42 Delta Nitrocarburized (4hrs) 4
Wear Volume 0.11 mm³



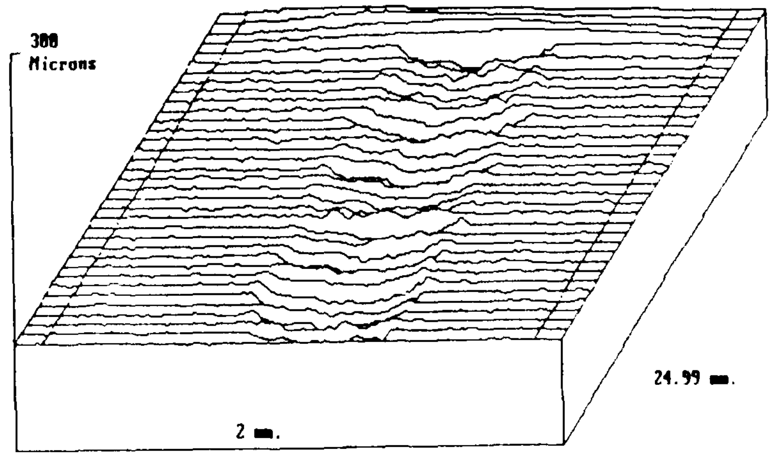
HSSA44 Plain Titanium
Wear Volume 7.54×10^{-2} mm³



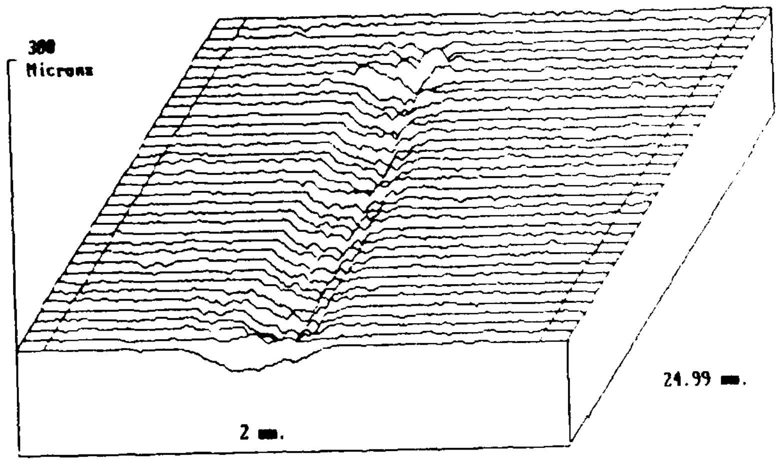
HSSA43 Delta Nitrocarburized (6hrs) 5
Wear Volume 0.00 mm³



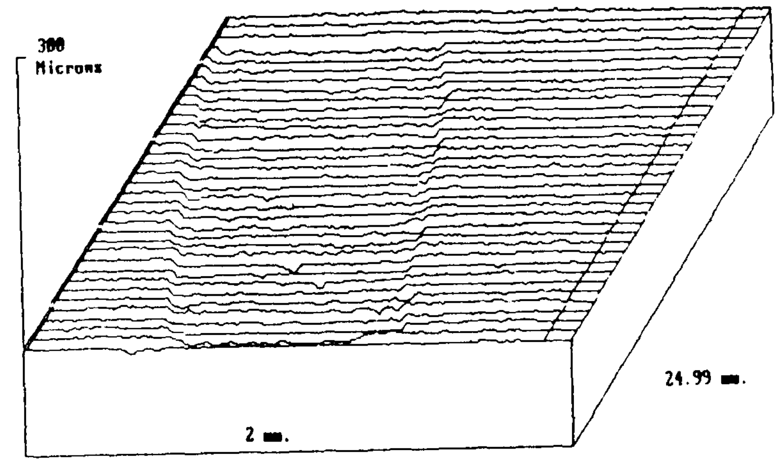
HSSA45 Beta Nitrocarburized 3
Wear Volume 4.11×10^{-2} mm³



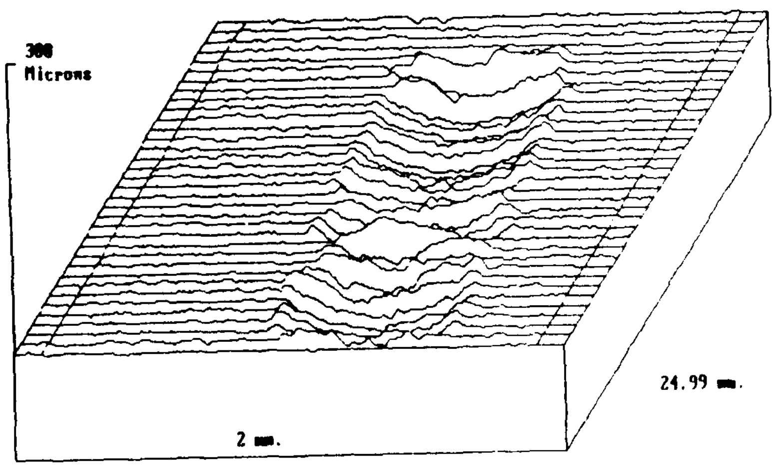
HSSA46 Delta Nitrocarburized 6
Wear Volume 9.32×10^{-2} mm^3



HSSA48 D Nitrocarburized + TiN (SIP)
Wear Volume 6.10×10^{-2} mm^3



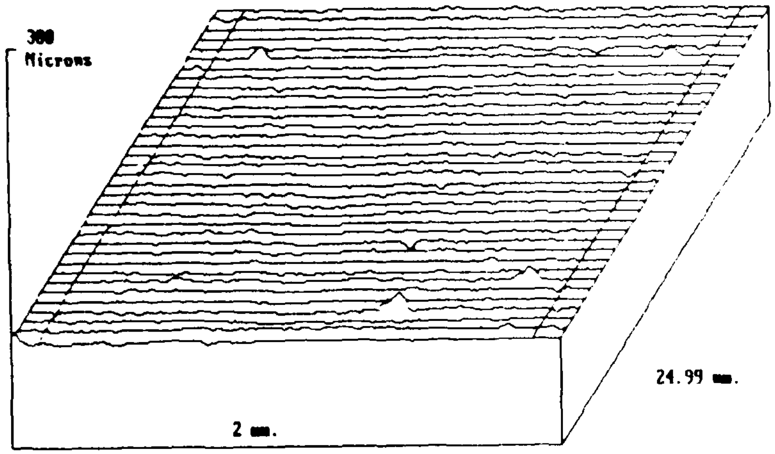
HSSA47 Carbonitrided 4
Wear Volume 8.78×10^{-2} mm^3



APPENDIX 8: 50N Wear Profiles of Wear Tracks in Nitrogen

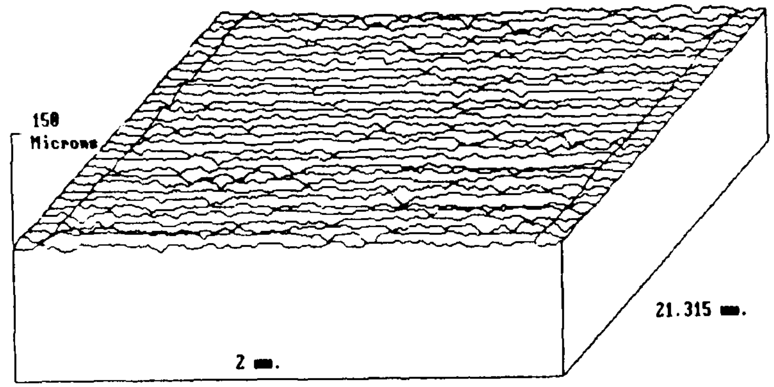
HSSA30 Beta nitrocarburized 2

Wear Volume 1.77×10^{-2} mm^3



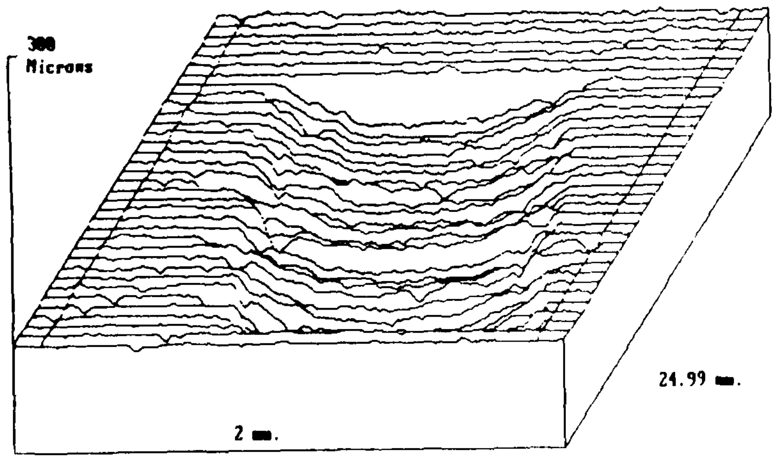
HSSA36 D Nitrocarburized + TiN (SIP) 1

Wear Volume 4.08×10^{-4} mm^3



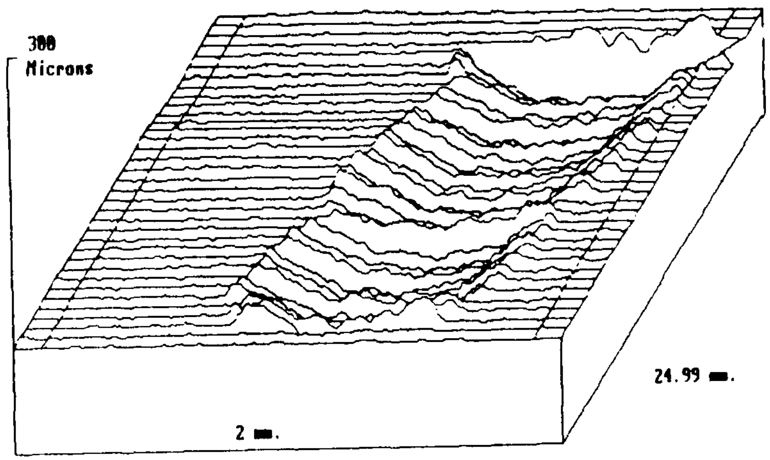
HSSA34 Carbonitrided 3

Wear Volume 0.54 mm^3

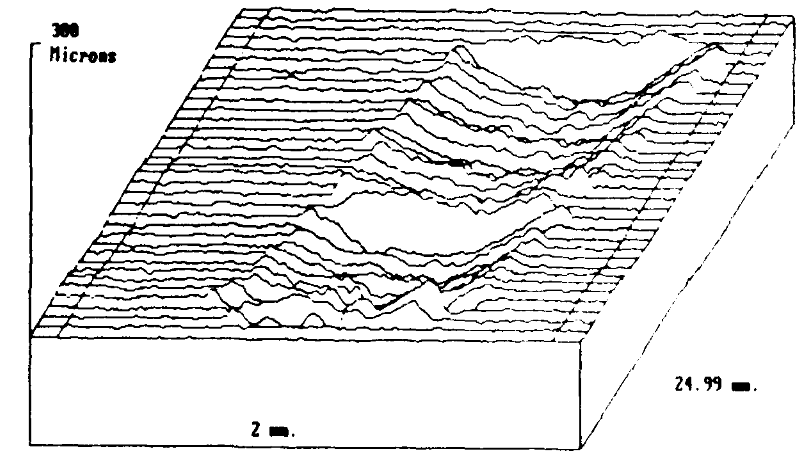


HSSA41 Delta Nitrocarburized (2hrs) 3

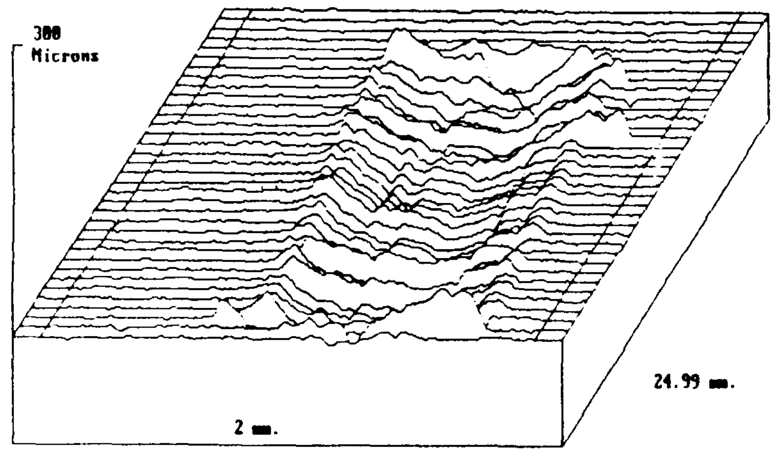
Wear Volume 0.26 mm^3



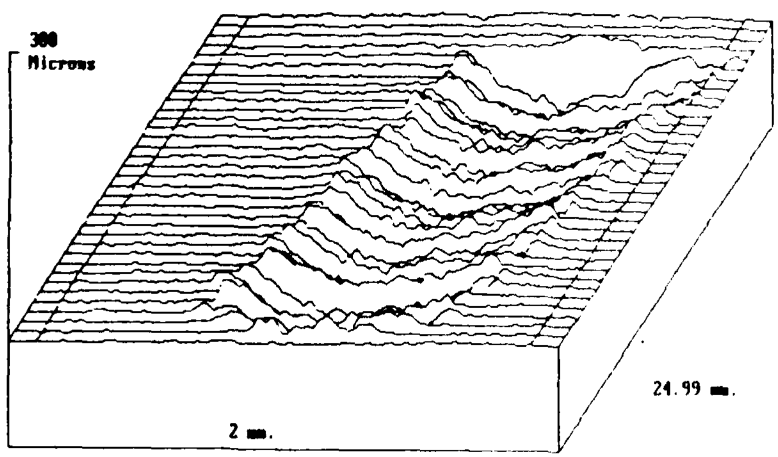
HSSA42 Delta Nitrocarburized (4hrs) 4
Wear Volume 0.25 mm^3



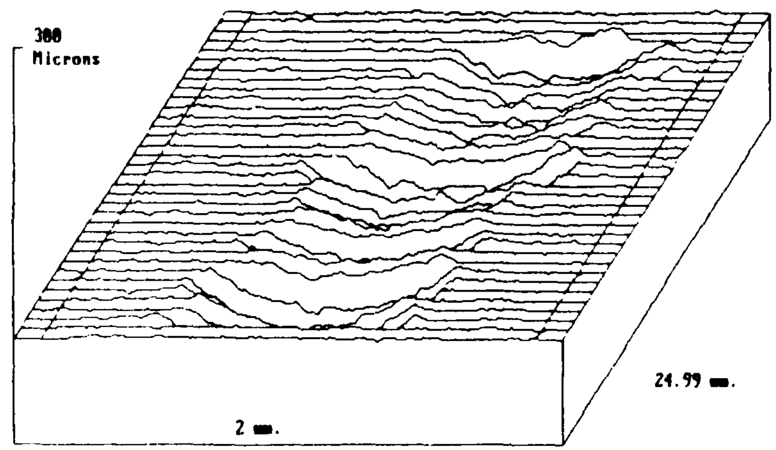
HSSA44 Plain Titanium
Wear Volume 0.18 mm^3



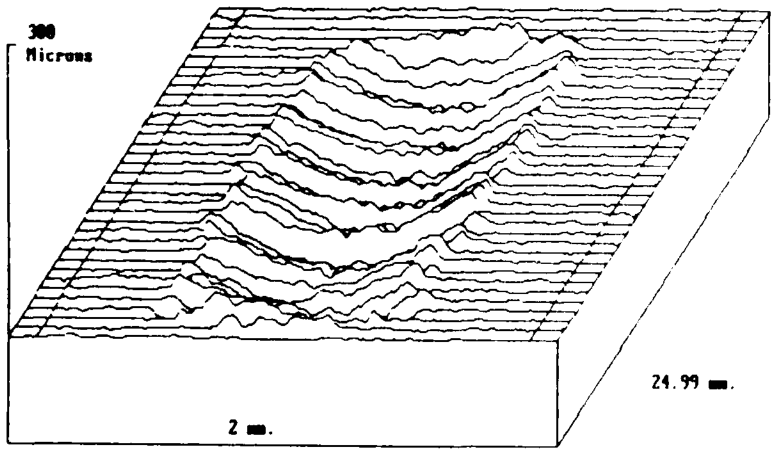
HSSA43 Delta Nitrocarburized (6hrs) 5
Wear Volume 0.22 mm^3



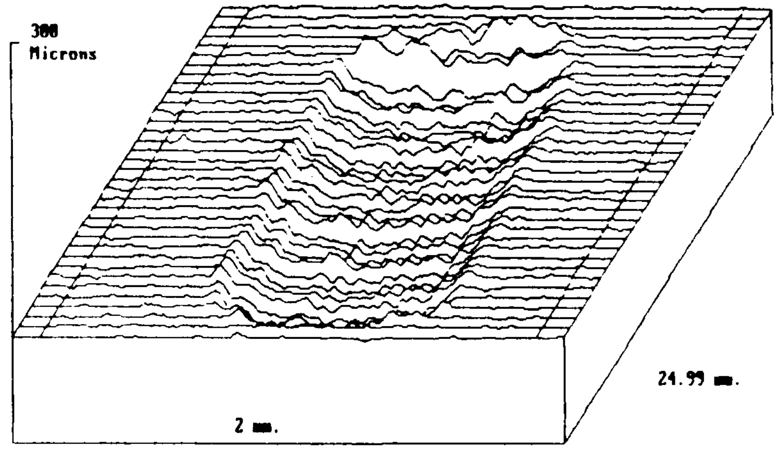
HSSA45 Beta Nitrocarburized 3
Wear Volume 0.22 mm^3



HSSA46 Delta Nitrocarburized 6
Wear Volume 0.23 mm^3



HSSA48 D Nitrocarburized + TiN (SIP)
Wear Volume 0.26 mm^3



HSSA47 Carbonitrided 4
Wear Volume 0.16 mm^3