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OAK RIDGE
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MARTIN MARIETTA

Engine Testing of Ceramic Cam-Roller Followers

Final Report

Y. Kalish

Prepared by
Detroit Diesel Corporation
Detroit, Michigan

CERAMIC TECHNOLOGY FOR
ADVANCED HEAT ENGINES

CERAMIC TECHNOLOGY PROJECT
DOE/ORNL

MANAGED BY
MARTIN MARIETTA ENERGY SYSTEMS, INC.
FOR THE UNITED STATES
DEPARTMENT OF ENERGY

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ENGINE TESTING OF CERAMIC CAM-ROLLER FOLLOWERS

Y. Kalish

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FINAL REPORT

Prepared by
Detroit Diesel Corporation
Detroit, Michigan
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ABSTRACT

The purpose of the project was to inspect and test 100 domestically produced silicon nitride cam-roller followers built to the requirements of the DDC Series 60 engine.

INTRODUCTION

For several years, DDC has been developing monolithic ceramic heat engine components. One of the components, developed for an application in our state-of-the-art on-highway, heavy-duty diesel engine, the Series 60, is a silicon nitride cam-roller follower (see Figure 1). Prior to starting this program, each valve train component in the Series 60 was considered for conversion to a ceramic material. Many advantages and disadvantages (benefits and risks) were considered. From this effort, one component was selected, the cam-roller follower. Using a system design approach, a ceramic cam-roller follower offered functional improvement at a reasonable cost.

Initially, two suppliers participated in ceramic cam-roller follower development, one domestic and one foreign. During the development process the domestic supplier elected to cease participation in the project. The main reasons for this action were: inability to make prototypes to specification; lack of funds to scale-up; and inability to define a production feasible, cost-effective process.

Recently two domestic suppliers expressed interest in DDC's effort. Furthermore, their materials appeared to meet DDC requirements. DDC has also developed expertise in statistical process capabilities and functional tests of silicon nitride rollers. In order to promote development of domestic ceramic engine component suppliers, this contract was awarded to DDC to inspect and test 100 domestically produced silicon nitride cam-roller followers for the Series 60 4-cycle, 275-450 hp diesel engine.

Research sponsored by the U.S. Department of Energy, Assistant Secretary for Conservation and Renewable Energy, Office of Transportation Technologies, as part of the Ceramic Technology Project of the Advanced Materials Development Program, under contract DE-AC05-84OR21400 with Martin Marietta Energy Systems, Inc., Work Breakdown Structure Subelement 3.3.1.8.

EXECUTIVE SUMMARY

0.1 Objectives

The objectives of this project were to inspect and test 100 domestically produced silicon nitride cam-roller followers built to the requirements of the Detroit Diesel Corporation's Series 60 4-cycle, 275-450 hp diesel engine. The inspection and functional laboratory tests were consistent with those previously performed on foreign produced cam-roller followers. Therefore, results from these efforts could also be compared with previous data from foreign produced ceramic rollers.

The tasks of the project are summarized in the following work statement.

0.2 Work Statement:

Task 1 Definition and Test of Production Feasible Cost-effective Process Flow Sheet

Identification of a high-volume, production feasible process flow sheet and fabrication of 50 consecutively produced wide and 50 consecutively produced narrow cam-roller followers. This task also includes dimensional and surface finish inspection of each part, and a statistical "process capability" calculation for each dimension.

Task 2 Functional Laboratory Tests

Overspeed capability test and a 100,000 equivalent mile accelerated wear test. Both tests were performed on a cylinder head rig. Results were compared to foreign produced silicon nitride cam-roller followers tested under the same conditions.

Task 3 Reporting

A detailed final report describing domestically produced silicon nitride cam-roller follower activities.

0.3 Conclusions

1. Process capability of the foreign produced silicon nitride cam-roller followers is higher than domestically produced cam-roller followers. In the case of foreign produced wide rollers, all ten parameters reviewed were acceptable or marginal, while only six were marginal or acceptable for the domestically produced wide rollers. Nine parameters out of ten were acceptable or marginal for the foreign produced narrow rollers. However, only two parameters for domestically produced narrow rollers were acceptable or marginal.

2. Both silicon nitride materials fabricated by the domestic sources of wide rollers and narrow rollers meet DDC requirements for the minimum and B-1 flexural strength. Average flexural strength of both domestically produced materials is higher than that of the foreign produced material. Weibull modulus of the material, fabricated by the supplier of wide rollers, is comparable to the foreign produced material. Weibull modulus of the material, fabricated by the supplier of the narrow rollers, is lower than that of the foreign produced material.

3. Wide rollers performed satisfactorily on the overspeed capability test. No failures were observed. However, two narrow rollers failed during the overspeed capability test. No foreign produced rollers ever failed on this test.

4. Two narrow rollers failed during the accelerated wear-out test. The camshaft was worn extensively under both wide and narrow rollers. Pin/roller clearance, which increases as either the roller ID or pin OD wears, increased during the test for both wide and narrow rollers. Practically no change in pin/roller clearance was observed for the foreign produced rollers, and no failures were observed.

5. Extensive wear of both wide and narrow rollers can be traced to dimensional nonconformance, caused by machining problems. Improvements in machining are necessary to decrease the wear rate.

6. Failures of the narrow rollers, on both overspeed capability and accelerated wear-out tests, also may be due to problems with material and/or the fabrication process. Failure of one MOR test bar due to a flaw and low sintered density of a failed roller support this conclusion.

7. Surface roughness of the OD and ID deserves additional attention. Surface roughness was within spec for the wide and narrow rollers and decreased on roller OD and ID during the wear-out test. Excessive initial surface roughness will lead to a failure. Therefore, determination of a surface roughness limit would be benefitial for controlling machining costs.

TASK 1 DEFINITION AND TEST OF PRODUCTION FEASIBLE COST-EFFECTIVE PROCESS FLOW SHEET

1.1 Fabrication Process

In order to evaluate both domestic suppliers it was decided to procure wide (23.45 mm width) and narrow (12.15 mm width) cam-roller followers from different suppliers. Wide rollers were fabricated by Supplier "A", and narrow rollers were fabricated by Supplier "B".

1.1.1 Supplier of Wide Rollers

Sintered SiAlON material was used to fabricate wide cam-roller followers. The fabrication process flow chart is shown in Figure 2.

A total of thirty-six (36) rollers and process control data for fifty (50) consecutively manufactured rollers were submitted to Detroit Diesel Corporation.

Rollers were crowned by the supplier internally on experimental tooling, since the outside machining source expected to do the crowning operation backed out of the project at a late date. This contributed to some nonconformance in ID-OD parallelism and OD roundness.

1.1.2 Supplier of Narrow Rollers

Dry pressed, gas pressure sintered silicon nitride material was used for the fabrication of narrow cam-roller followers. The fabrication process flow chart is shown in Figure 3.

A total of seventy-nine (79) narrow silicon nitride ceramic cam-roller followers were fabricated. During final measurement of component properties, an accident occurred. Rollers #01 through #49 were dropped from a measurement bench and forty (40) of these rollers sustained chip damage. Detroit Diesel Corporation approved acceptance of thirty-six (36) rollers and the data for all seventy-nine (79).

1.2 Quality Audit

1.2.1 Procedure for Calculation of Percent Process Capability

Detroit Diesel Corporation used procedures outlined in [1] for the calculation of percent process capability. The Process Capability (PC) is equal to six standard deviations, as calculated from component measurements, i.e.:

$PC = 6s$
where $s = R/d_2$
and $R = R/n_s$
where R is the sample range (maximum - minimum dimension in a sample)

n_s is the number of rational subgroups (we usually use 10 rational subgroups, with 5 samples in each)

d_2 is a Shewhard constant ($d_2 = 2.326$ for the subgroup size of 5)

Therefore, percent process capability, PC%, can be expressed as:

$$PC\% = \frac{6s * 100\%}{\text{spec. tolerance}}$$

Processes with PC% of less than 70% are considered acceptable, between 70% and 100% - marginal, and a PC% of more than 100% is unacceptable.

This procedure was used to evaluate dimensional capability of foreign and domestically produced rollers.

1.2.2 Comparison of % Process Capability for Domestic and Foreign Produced Rollers

Percent process capability was calculated for the following ten key characteristics: OD size; ID size; width; OD finish; ID finish; OD roundness; ID roundness; OD crown; ID-OD parallelism; and ID-OD runout. Results are shown in Figure 4.

Both narrow and wide cam-roller followers, fabricated by one foreign supplier, were tested at DDC. Results show that, in general, it is more difficult to meet dimensional requirements for the narrow rollers than requirements for wide rollers.

Both domestic suppliers fell short of achieving the process capability of the foreign supplier. For wide rollers, all dimensions on the foreign produced rollers were acceptable (percent process capability was within the internal DDC requirement of 70% for all ten characteristics). Domestically produced wide rollers had only 5 acceptable characteristics, 1 marginal and 4 were unacceptable. For narrow rollers, only 4 characteristics on the foreign produced rollers were acceptable, 5 were marginal and 1 was unacceptable. Domestically produced narrow rollers had only 2 acceptable characteristics, and five characteristics were unacceptable. Since a go/no-go gage was used for three other parameters, we could not calculate percent process capability for them.

1.2.3 Flexural Strength

According to DDC's ceramic cam-roller follower material specification [2], the minimum flexural strength of the roller must be 420 MPa, determined by a four-point bend test at room temperature. Test bar specimens have the following dimensions: 60mm long x 4mm wide x 3mm thick. The supplier is required to perform the flexural strength test on a fourteen (14) piece sample for every new lot of material. The B-1 MOR strength must be at least 380 MPa, calculated using two parameter Weibull statistics and least square linear regression, on a minimum of fourteen median ranked MOR samples.

Wide rollers were fabricated from one powder lot and one sintering run. Therefore, wide rollers represent one material lot, #A010202. Data for a total of 25 test bars was submitted and statistically processed at DDC. Results are shown in Figure 5. The material meets DDC specification for MOR strength. Weibull modulus for 25 bars was 16.

Two different powder lots (90L-998 and 91A-004) were utilized for the fabrication of narrow rollers. Three different sintering runs (90L-998, 91A-004A, 91A-004B) were performed. Therefore, narrow rollers represent three different material lots. Data for a total of 42 test bars (14 for each material lot) was submitted and statistically processed at DDC. Combined results for three lots are presented in Figure 6. The Weibull moduli for three lots were different : 7.5 for lot #91A-004B; 17 for lot #90L-998; and 32 for lot #91A-004A. The Weibull modulus for all 42 test bars was 10. The low Weibull modulus of lot

#91A-004B was due to test bar #13. Fractography was performed on this specimen and the failure origin was found to be a near surface agglomerate/pore cluster.

Figure 7 shows the comparison of the flexural strength for three silicon nitrides; (1) foreign produced; (2) wide roller domestic material; and, (3) narrow roller domestic material. Data for 150 MOR test bars was statistically processed for the foreign produced material.

The average strength of both domestic ceramic materials is higher than that of foreign material. However, based on all MOR bars tested, both foreign and domestic, the lowest strength sample was a domestic material, fabricated by the supplier of narrow rollers. The Weibull modulus of the domestic wide roller material is comparable to that of foreign produced silicon nitride. It may decrease, though, for production quantities of material. If it does not, the domestic material could have a high Weibull modulus and a flexural strength higher than required for this application . This could lead to a future cost savings. The Weibull modulus of the narrow rollers material is much lower than that of the foreign produced silicon nitride. Due to the high average flexural strength, narrow rollers material still met DDC requirements for minimum and B-1 strength, despite the low Weibull modulus.

Changes in the pin/roller clearances, weights of the rollers, and camshaft wear are quantified in Figure 22. Measurements showed that some rollers actually gained weight. This was caused by carbon deposits from the oil on the ID of the rollers.

None of the foreign produced rollers, wide or narrow, failed during the overspeed capability or accelerated wear-out tests. During the program, domestic ceramic rollers wore more than foreign rollers. Figures 23 and 24 compare the change in pin/roller clearance for wide and narrow domestic and foreign rollers.

Post test evaluation was performed by the suppliers. Separate reports for overspeed capability and accelerated wear-out tests were submitted by the supplier of wide rollers. The supplier of narrow rollers submitted one report that covered both tests.

2.2 Post Test Evaluation of the Wide Rollers

2.2.1 Overspeed Capability Test

Two rollers, along with the corresponding roller pins (sets #77 and 80), were evaluated after the overspeed capability test. Of major concern was discoloration and wear evident on the metal roller pins.

Visual review of roller/pin set #77 found very little indication of wear on the roller OD. The roller ID had a visible dark band, indicating wear had occurred near the center of the part (see Figure 25a). The pin had also sustained wear in the center (see Figure 25b).

A Rank Taylor Hobson Form Talysurf was used to analyze the wear on the roller ID. A surface trace was run from end to end on the ID. This trace is shown in Figure 26. The surface profile indicates that the ID is slightly "bell mouthed". Also, the character of the surface profile in the center of the roller reflects the wear that occurred during testing. Peak heights at the center are somewhat reduced compared to the finish at either end.

TASK 2 FUNCTIONAL LABORATORY TESTS

2.1 Results of the Tests

An outline of the overspeed capability test is shown in Figure 8. It consists of nine (9) engine RPM levels, from 3300 to 4100 RPM. (Note: the Series 60 rated speed is 2100 RPM). Nine wide rollers were tested - six in the injector rocker arms and three in the exhaust rocker arms. All wide rollers completed the test. Nine narrow rollers were tested - six in the intake rocker arms and three in the exhaust rocker arms. Two narrow rollers in exhaust rocker arm positions failed during the test, both on the third RPM level (see Figure 9). Three narrow rollers, including two that failed, and two wide rollers were returned to their suppliers for evaluation after the overspeed test was completed.

An outline of the accelerated wear-out test is shown in Figure 10. It consists of seven (7) cycles, and corresponds to running the engine for 100,000 equivalent miles. Nine wide rollers were tested - six in the injector rocker arms and three in the exhaust rocker arms. All wide rollers completed the test. Nine narrow rollers were tested - six in the intake rocker arms and three in the exhaust rocker arms. Two narrow rollers in the exhaust rocker arm positions failed during the test. One failed during the first cycle (see Figure 11) and another during the seventh cycle (see Figure 12). Three narrow and two wide rollers (including two failed narrow rollers) were returned to the suppliers for the post test evaluation.

Wide rollers and pins that successfully completed accelerated wear-out test are shown on Figures 13 and 14. Narrow rollers and pins that successfully completed the accelerated wear-out test are shown in Figures 15 and 16. Cam lobes on the Series 60 camshaft used in this test were extensively worn, see Figure 17. The most wear occured on injector lobes (see Figure 18) under wide ceramic rollers and exhaust lobes under narrow ceramic rollers (see Figure 20). Less wear occured on intake lobes (see Figure 19) under narrow ceramic rollers and exhaust lobes under the wide ceramic rollers (see Figure 21).

Figures 27 and 28 are higher resolution profiles of sections from the profile shown in Figure 26. Figure 27 is a section taken near the edge of the roller, and Figure 28 is a section taken in the wear area at the center of the part. There is a subtle difference in the surface traces, the wear area shown in Figure 28 has more truncated peaks and a predominance of valleys in the surface profile. The data that accompanies each trace verifies perceived differences. Note that the Ra value in Figure 27 (near the edge) is .204 um. In the wear area (Figure 28) the Ra is .171 um. The Rp and Rpm values, a measure of peak height above the profile mean, reflect the reduced peak height in the wear area.

Roller #77 was sectioned and submitted for Scanning Electron Microscope (SEM) analysis. Figure 29 represents photomicrographs from this analysis showing the ID wear area at 50x, and 250x. A porous surface is evident. The apparent elongation of the pores indicates some spalling and bridging between pores has occurred in the wear area. The horizontal lines seen on the first (Figure 29a) are grinding marks.

The OD of roller #80 appeared to have sustained more wear during testing than #77. The witness mark left from contact with the cam tracked unevenly around the circumference of the roller. This condition is related to ID-OD parallelism. The measured value of 0.02 mm is greater than the print specification of .01 mm. This nonconformance is documented by the Initial Sample Inspection Report that was submitted to DDC with this part. Figure 30a is a 2x photograph of the wear mark. Figures 30b and 30c are photographs of the wear on the roller ID and the roller pin.

The #80 roller ID was analyzed with the Form Talysurf instrument. Figure 31 is a trace of the surface profile of the ID from end to end. Again, the profile indicates some bell mouthing is present, with the center of the part raised in relation to the ends. However, this condition appears to be less symmetrical on roller #80 than it was on #77. The expanded profile sections and data presented in Figures 32 and 33 indicate that wear occurred in the raised center of the ID.

Roller #80 suffered the most severe burnishing of the two wide rollers analyzed by the supplier after completion of the overspeed capability test. Inspection documents indicated that this part was not to print and shipped under deviation for ID-OD parallelism. This condition was the result of the crowning operation employed by the supplier. The ID-OD parallelism was in specification prior to the crowning operation. As mentioned earlier, the supplier of the wide rollers was forced to crown the rollers internally.

The profile traces indicate a small degree of bell mouthing on the roller IDs, 0.0001" to 0.0002". This was not detected during the initial inspection. However, in the post test analysis, using precision bore gages, suggested a slight degree of bell mouthing. This may have contributed to the burnishing of the roller pins. This condition could be the result of precision honing operations used during ID finishing.

The visual low density band seen on the wide rollers appears to have caused no wear problems in the overspeed capability test. No measurable wear was noted on the crowns of the returned pieces.

Profile traces were run on the steel pins returned with the ceramic rollers. Pins measure straight and round.

2.2.2 Accelerated Wear-out Test

Two rollers and the corresponding pins #8 and #55, run on the accelerated wear-out test, were subject of the post test evaluation by the supplier.

Visual review of roller/pin set #8 found very little indication of wear on the roller OD. The roller ID had a visible dark band indicating wear had occurred near the center of the part. Also, the pin had sustained wear visible in the center of its OD.

The Rank Taylor Hobson Form Talysurf was used to analyze the wear on the ID of the roller. A surface trace was run from end to end on the ID. The surface profile indicates that the ID is slightly bell mouthed. Also, the surface finish in the center reflects the wear that occurred in testing, peak heights are somewhat reduced compared to the finish at either end of the roller. There is a subtle difference in the surface traces near the edge of the roller and at the center of the part. The wear area near the center of the part has more truncated peaks and a predominance of valleys in the profile. The Ra value near the edge of the roller is .110 um, and in the wear area the Ra is .090 um. Also, the Rpm values, a measure of peak height above the profile mean, reflect a reduced peak height in the wear area.

A surface trace from the OD was also analyzed. As with the ID, a slight amount of wear was present. Near the edge of the roller the roughness average was .149 um Ra, and the peak height average above the mean was .413 um Rpm. Near the center of the roller, these values were reduced to .119 um Ra and .345 um Rpm, respectively.

Roller/pin set #55 was examined for wear using the Form Talysurf instrument. The inside diameter of this roller showed no wear. Two surface roughness traces were made on this part. One trace was made near the end of the ID, and a second trace near the center. There was no difference in the appearance of the traces or in the roughness data.

The outside diameter of roller #55 was examined for wear. Again two surface roughness traces were made, one near the edge, and one near the center. Some wear was detected. A reduction in the roughness average from .138 um, near the end, to .086 um, near the center indicated wear. Also, a reduction in the average peak height above the mean line, from .310 um to .186 um, tended to confirm the wear near the center of the OD.

2.3 Post Test Evaluation of the Narrow Rollers

Three narrow rollers from each of functional tests were returned to the supplier of narrow rollers for post test evaluation. These rollers were evaluated visually, dimensionally, for surface roughness (of roller OD and ID and pin OD), and with a profileometer to measure OD crown height and symmetry.

The two failed rollers from the overspeed capability test had one OD edge spalled along the entire circumference. The spalling ran roughly 2.00 mm (12 mm total width) across the OD, and 5 mm down the side of the roller (9 mm total thickness). These rollers, #65 and #67 were taken off the overspeed capability test after the third (of nine) RPM step. The two failed rollers from the accelerated wear-out test had very different failure modes. Roller #69 had a large single spall that ran from the OD to the ID of the roller, while roller #77 had a chipped flake removed from the OD surface - 6.3 mm long x 4.2 mm wide x 0.01 mm deep. Roller #77 failed during the first of seven cycles while #69 failed during the seventh cycle.

The visual condition on the ID of the rollers varied from "unused" to extensive dark discoloration. The extent of this discoloration on roller ID generally indicated the extent of wear on the OD of the pins. However, the ID's of the rollers did not show any spalling or flaking of corners or running surfaces. Therefore, the ID condition was not a precondition for the failure of the OD. There was no discernible difference in the OD and ID dimensions after testing, compared to pretest dimensions. However, the surface roughness on the OD of the rollers that passed each test was significantly lower than the surface roughness of the failed rollers. Where there was discoloration on the roller ID, the surface was smoother in three of the six samples, stayed the same in two samples, and was made noticeably rougher in only one sample - #65. The ID of sample #65 had small processing pits that were enlarged by wear during the accelerated wear-out test. The pin wear was characterized by an increase in surface roughness that ranged from 0.07 um to 0.27 um.

The profile of the crown on the OD of the rollers (see Figures 34 and 35) appears to be the most influential property that determines whether a roller passed or failed a given test. Narrow rollers returned by DDC to the supplier, that had passed a given test, had a crown of at least 50 microinches (0.0013 mm) (Figures 34a and 35a). Three rollers that had edge spalls had crowns of less than 30 microinches (0.0008 mm) (Figures 34b, 34c and 35b). Narrow roller #77 had a symmetrical crown of 40 microinches (0.0010 mm) (Figure 35c). Its spall, that ran across the surface of the OD, was most likely caused by low sintered density (3.125 g/cc vs typical 3.22 g/cc). Roller #60 from the accelerated wear-out test showed hardly any visual wear on the OD and ID, and it passed the test. It also has the highest density of the six rollers returned for the post test evaluation, 3.226 g/cc (theoretical density = 3.25 g/cc). Roller #60 has a pronounced peak to its OD profile, with a 60 microinch (0.0015 mm) rise at the center of the roller.

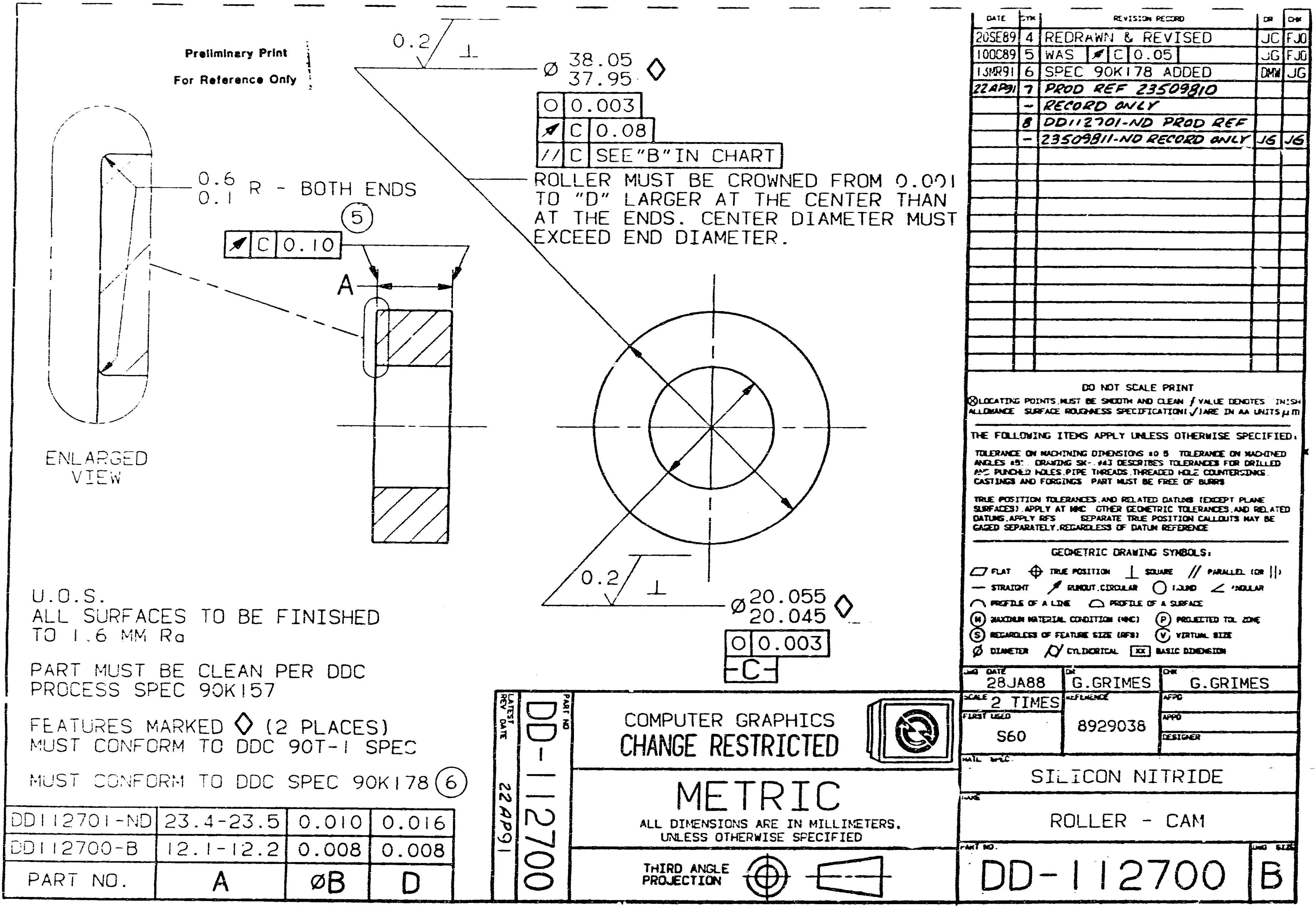
After examining the various dimensions and characteristics of failed and passed narrow cam-roller followers, there are three features that stand out as the prime cause of OD chipping and spalling. The most important causes of spalled edges was a crown of less than 40 microinches (0.0010 mm), at the low end of the spec limit, and/or poor symmetry of the roller crown. Low density of the sintered Si_3N_4 roller can also lead to spalling of the load bearing surface of the OD. Surface roughness must also be kept to as low a level as possible, below 6.00 microinch (0.15 um), as indicated by these preliminary results.

A characteristic that did not correspond to spall type failure was out-of-roundness. Those rollers that passed each type of DDC test had out-of-roundness that exceeded that of three of the four failed rollers.

REFERENCES

1. General Motors Manufacturing Systems Qualification Manual. General Motors Corporation, January 1987

2. Detroit Diesel Corporation Material Quality Specification #90K178 "Material Acceptance Criteria for Series 60 Silicon Nitride Cam Rollers", rev. 6-24-91



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10OC89	5	WAS ↗ C 0.05	JG	FJO
13MR91	6	SPEC 90K178 ADDED	DMW	JG
22AP91	7	PROD REF 23509810		
	-	RECORD ONLY		
	8	DD112701-ND PROD REF		
	-	23509811-ND RECORD ONLY	JG	JG

PART NO.	A	ØB	D
DD112701-ND	23.4-23.5	0.010	0.016
DD112700-B	12.1-12.2	0.008	0.008

Figure 1: Ceramic Cam-Roller Follower Drawing

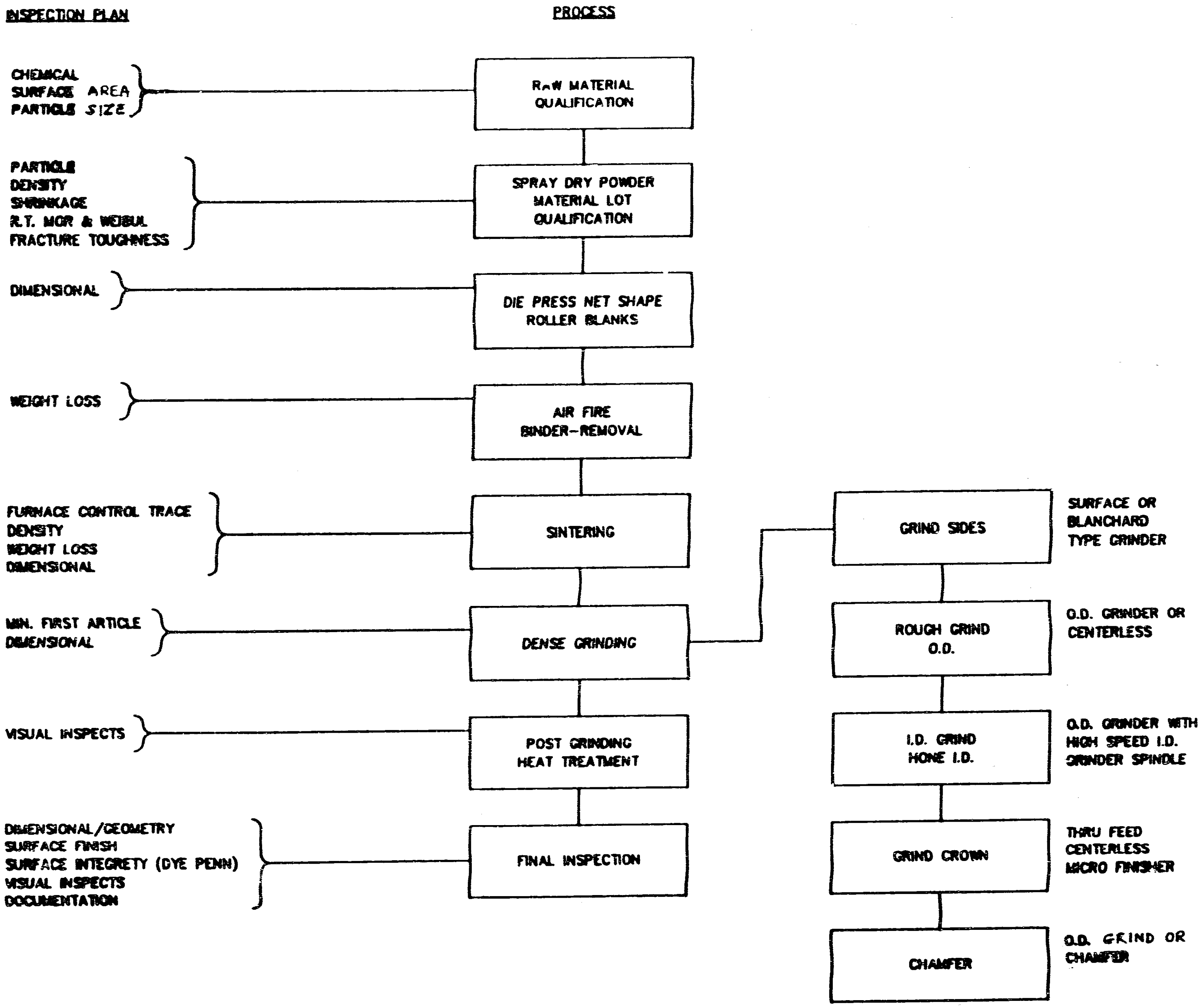


Figure 2: Wide Roller Process Flow Chart

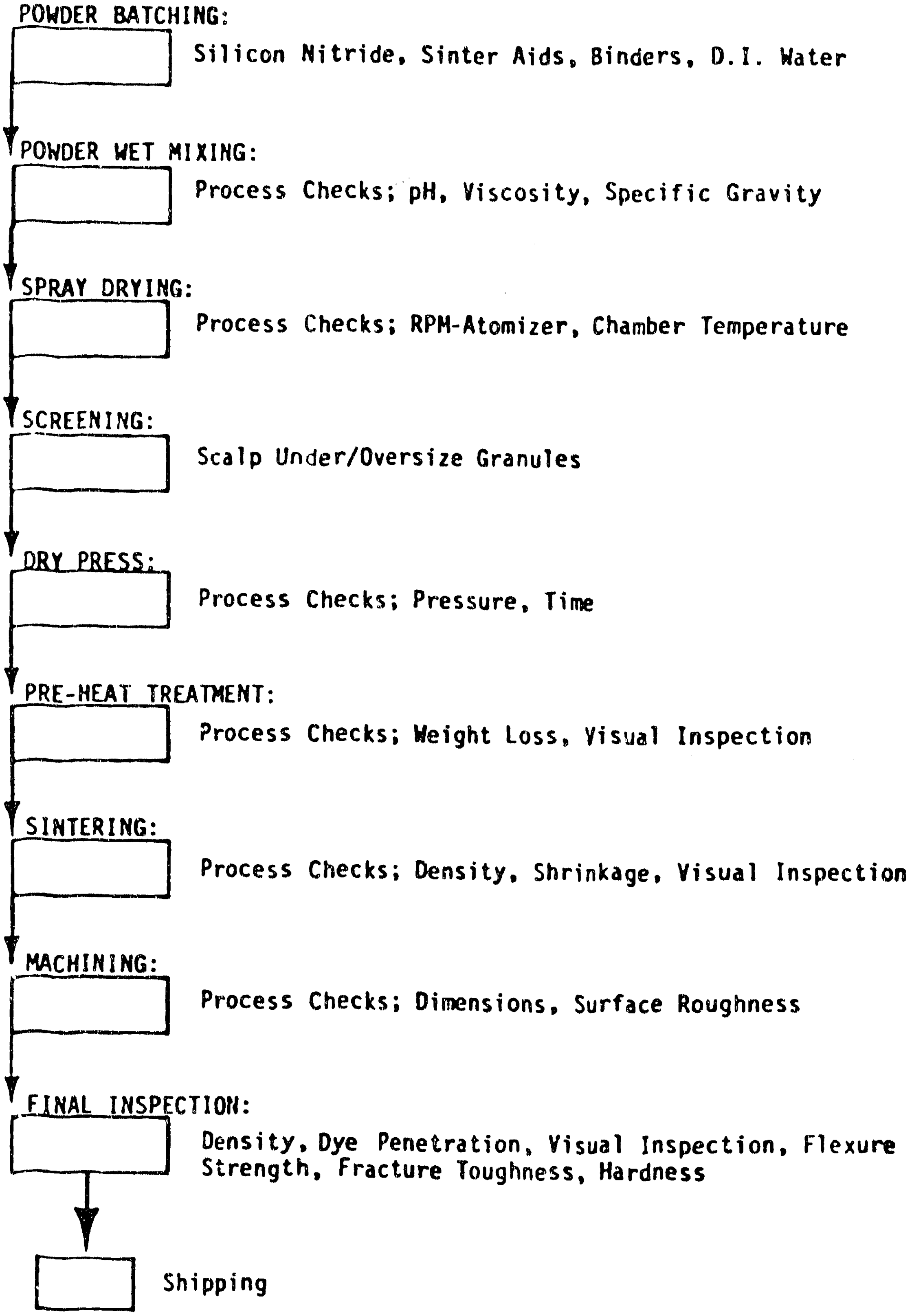


Figure 3: Narrow Roller Process Flow Chart

Series 60 Ceramic Rollers - Wide

Feature	Total Tolerance (mm)	Kyocera's % Process Capability	Domestic % Process Capability
OD size	0.10	50 (+)	56 (+)
ID size	0.01	70 (+)	151 (-)
width	0.10	62 (+)	38 (+)
OD finish	0.2	63 (+)	43 (+)
ID finish	0.2	36 (+)	108 (*)
OD roundness	0.003	53 (+)	136 (-)
ID roundness	0.003	69 (+)	131 (-)
OD crown	0.015	46 (+)	32 (+)
ID,OD parallelism	0.01	52 (+)	417 (-)
ID,OD runout	0.08	7 (+)	41 (+)
Totals	Acceptable (+)	10	5
	Marginal (*)	0	1
	Unacceptable (-)	0	4

Series 60 Ceramic Rollers - Narrow

Feature	Total Tolerance (mm)	Kyocera's % Process Capability	Domestic % Process Capability
OD size	0.10	63 (+)	34 (+)
ID size	0.01	114 (-)	145 (-)
width	0.10	77 (*)	34 (+)
OD finish	0.2	80 (*)	127 (-)
ID finish	0.2	31 (+)	??
OD roundness	0.003	79 (*)	394 (-)
ID roundness	0.003	83 (*)	727 (-)
OD crown	0.007	33 (+)	??
ID,OD parallelism	0.008	88 (*)	??
ID,OD runout	0.08	12 (+)	117 (-)
Totals	Acceptable (+)	4	2
	Marginal (*)	5	0
	Unacceptable (-)	1	5
Note: ??, won't be remeasured (a go and no-go gage was used)			

Figure 4. Percent process capability comparison

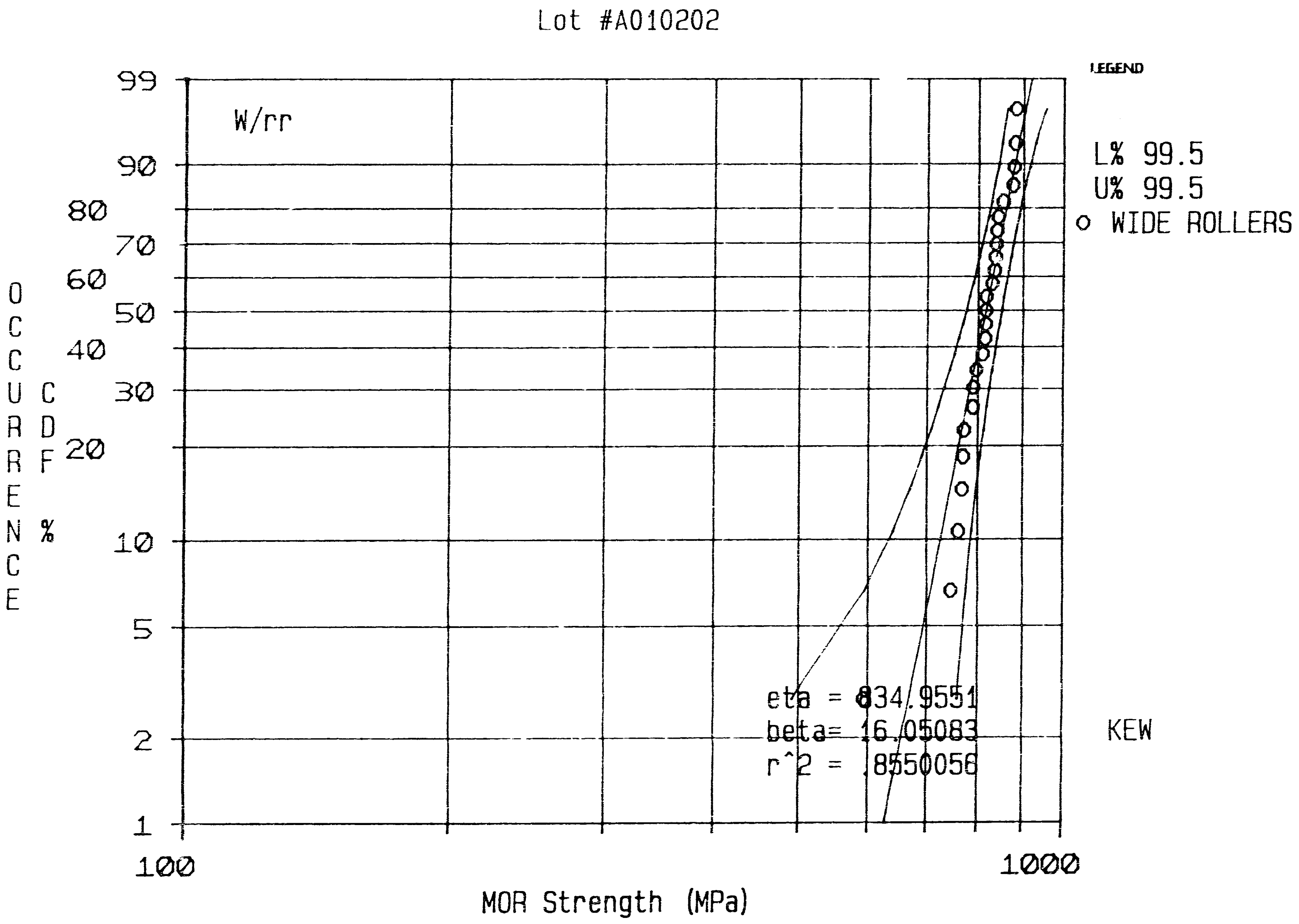


Figure 5: Wide Roller Flexural Strength

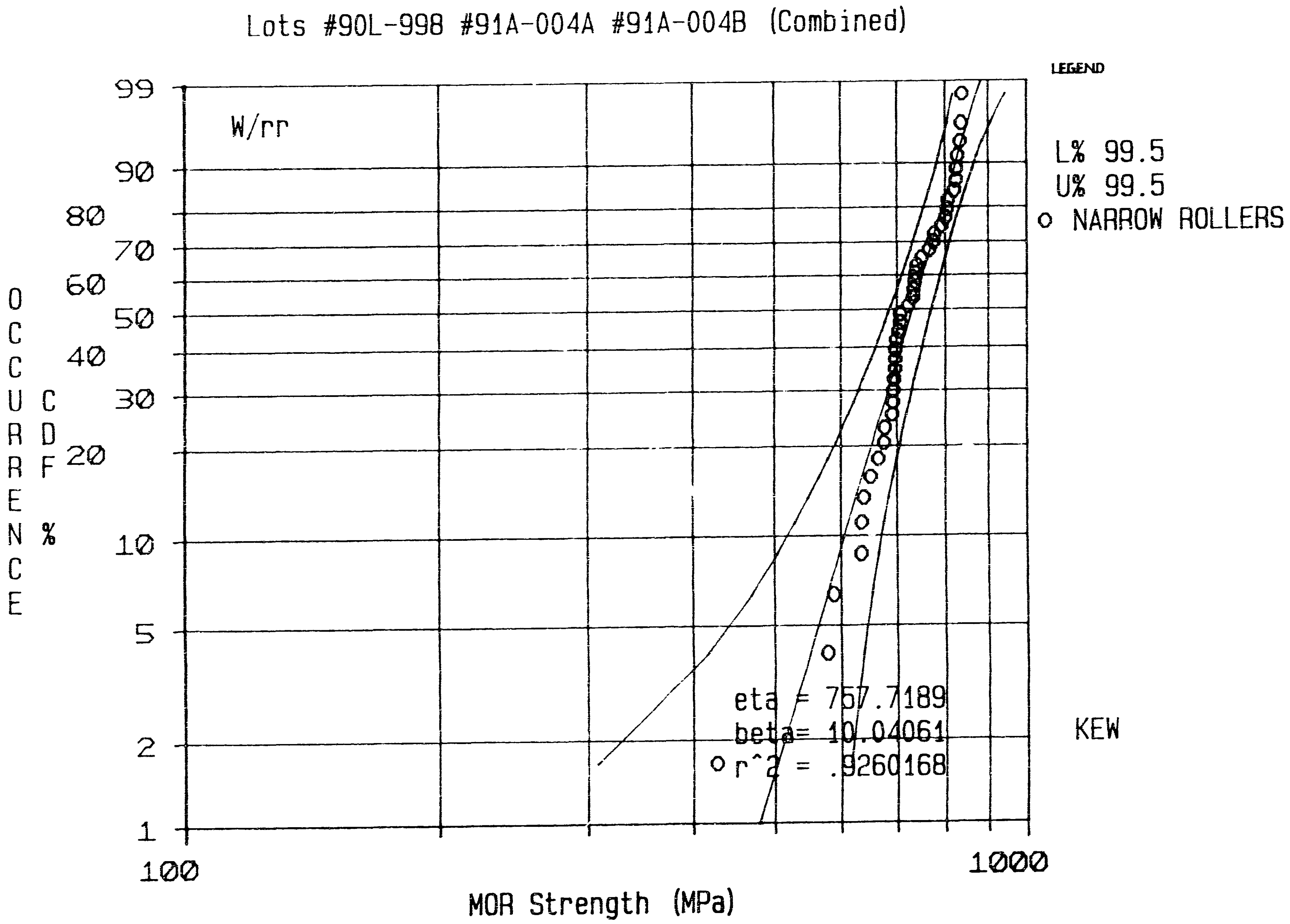


Figure 6: Narrow Roller Flexural Strength

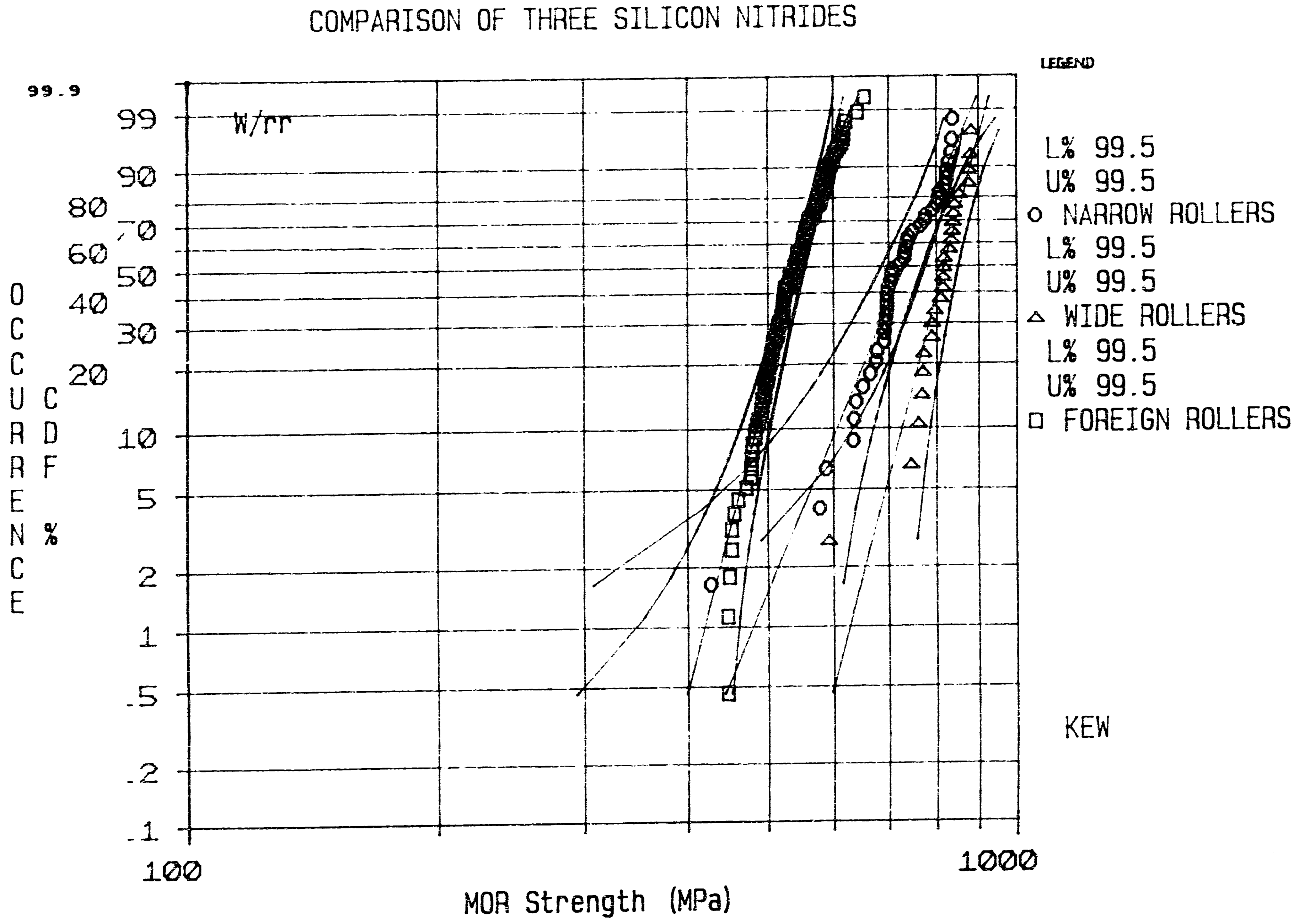


Figure 7: Flexural Strength Comparison

5.0 hrs @ 3300 rpm, .004 lash
4.9 hrs @ 3400 rpm, .004 lash
4.8 hrs @ 3500 rpm, .004 lash
4.6 hrs @ 3600 rpm, .004 lash
4.5 hrs @ 3700 rpm, .004 lash
4.4 hrs @ 3800 rpm, .004 lash
4.3 hrs @ 3900 rpm, .004 lash
4.2 hrs @ 4000 rpm, .004 lash
4.1 hrs @ 4100 rpm, .004 lash

Figure 8. Overspeed Capability Test

Figure 9: Rollers Failed on Overspeed Capability Test

Fixture is run on the following cycle 7 times:

1 minute at 600 cam-rpm, no oil pressure,
room temperature oil, idle injection load

5 minutes at 600 cam-rpm, 10 psi oil pressure,
room temperature oil, idle injection load

32 hours at 600 cam-rpm, 30 psi oil pressure,
230°F temperature, full injection load

12-14 hours shutdown for oil drain and inspection

Figure 10. Accelerated wear-out test

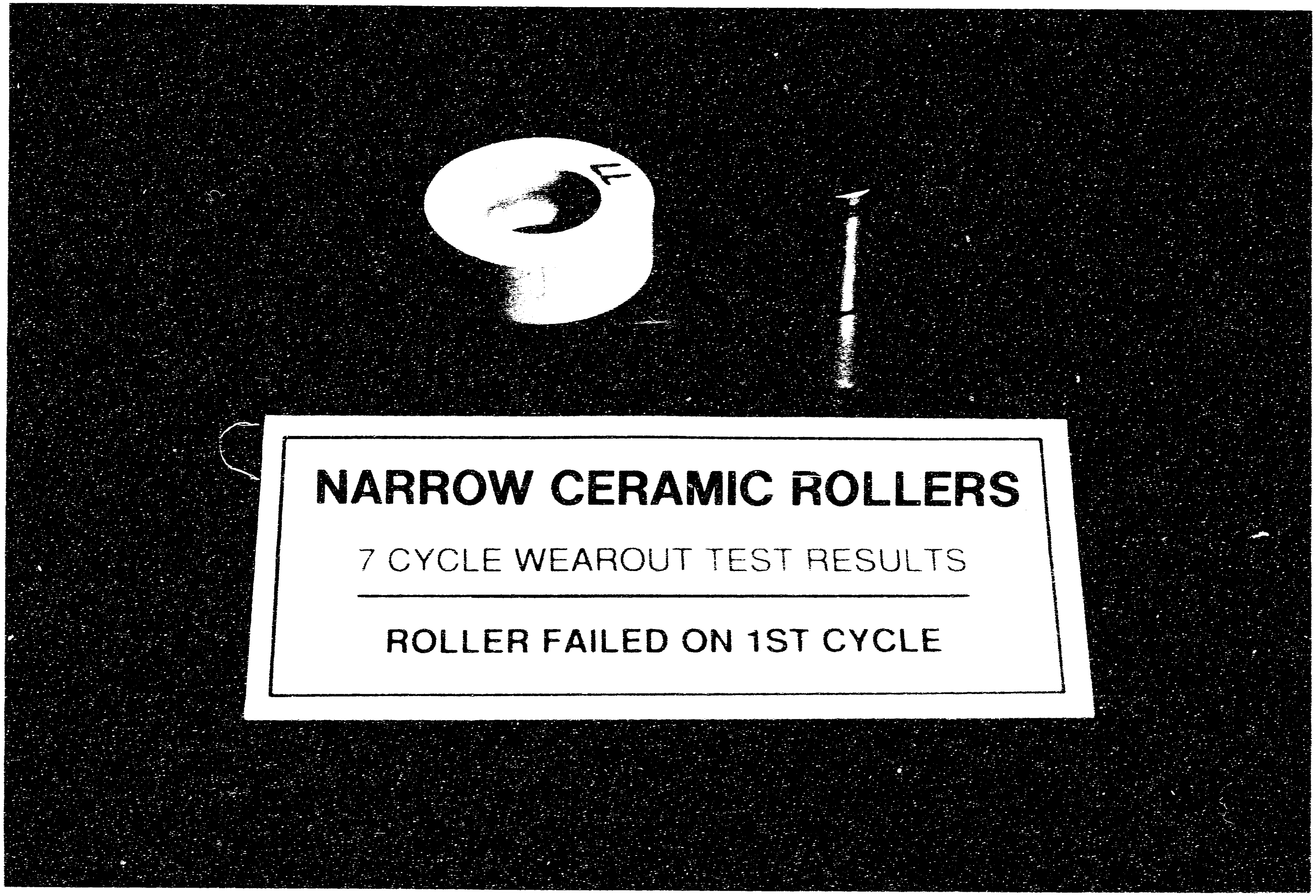


Figure 11: Roller Failed on the 1st Cycle of Accelerated Wear-Out Test

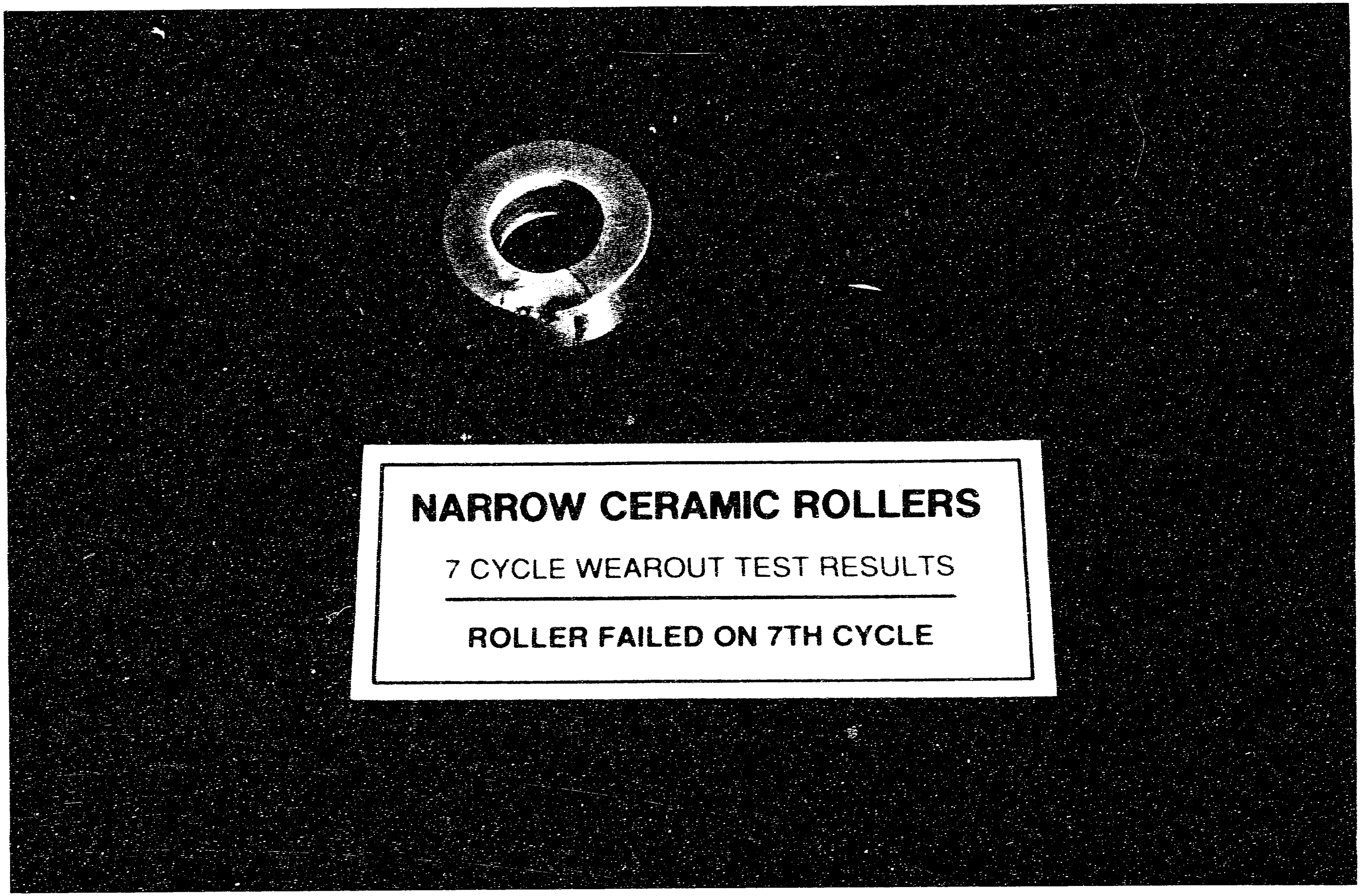


Figure 12: Roller Failed on the 7th Cycle of Accelerated Wear-Out Test

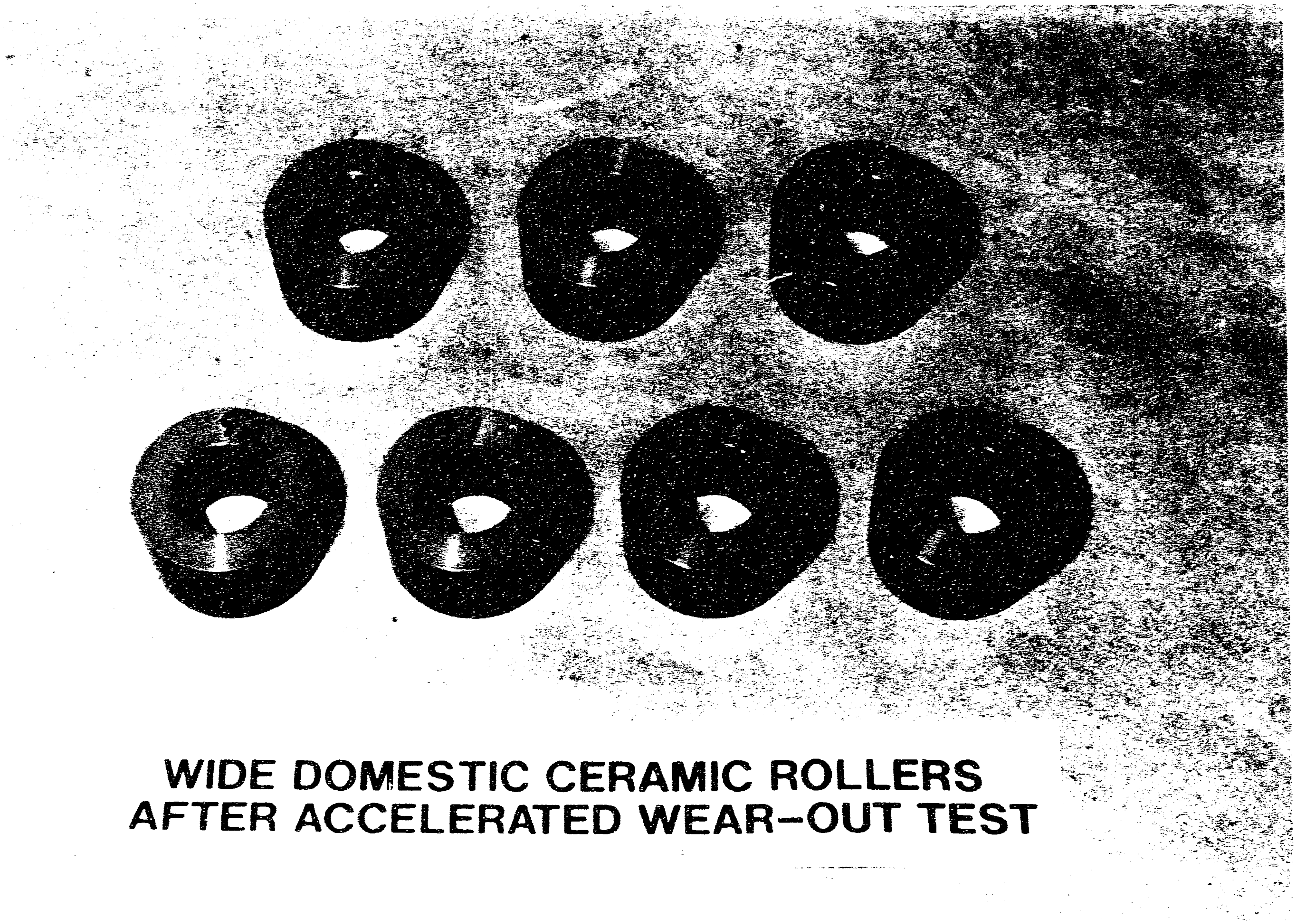


Figure 13: Wide Rollers that Successfully Completed the Accelerated Wear-Out Test

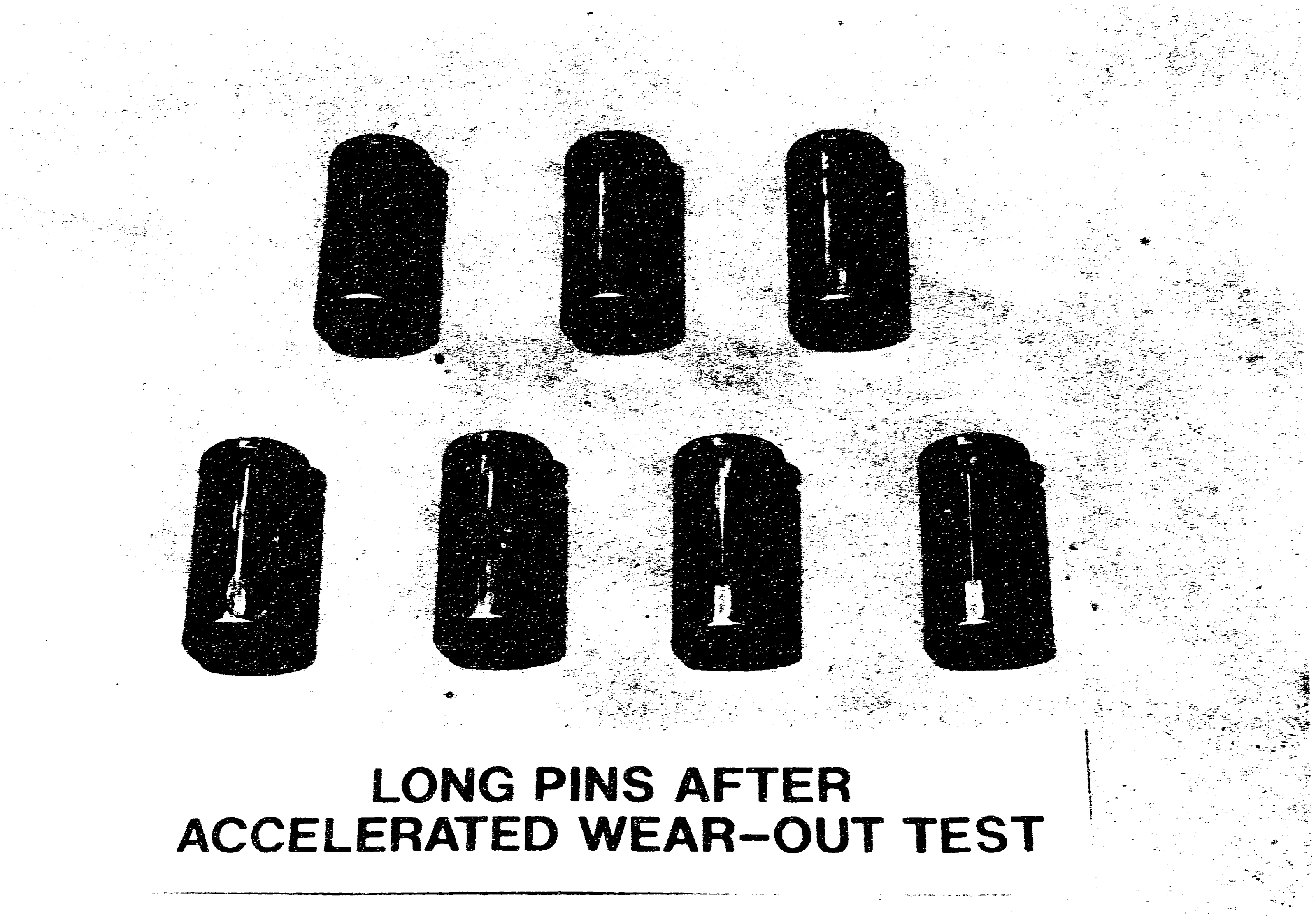


Figure 14: Pins from the Wide Rollers that Successfully Completed the Accelerated Wear-Out Test

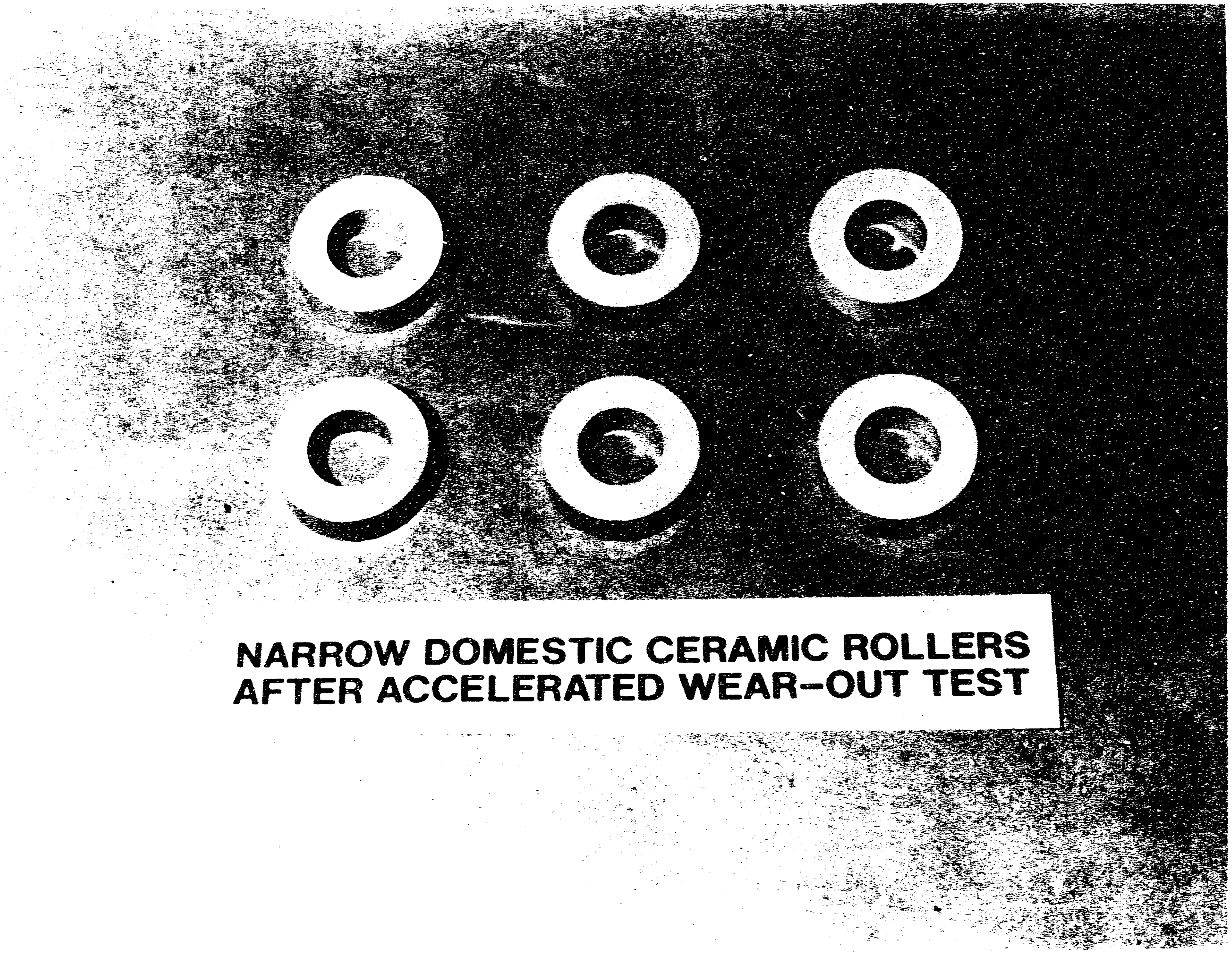


Figure 15: Narrow Rollers that Successfully Completed the Accelerated Wear-Out Test

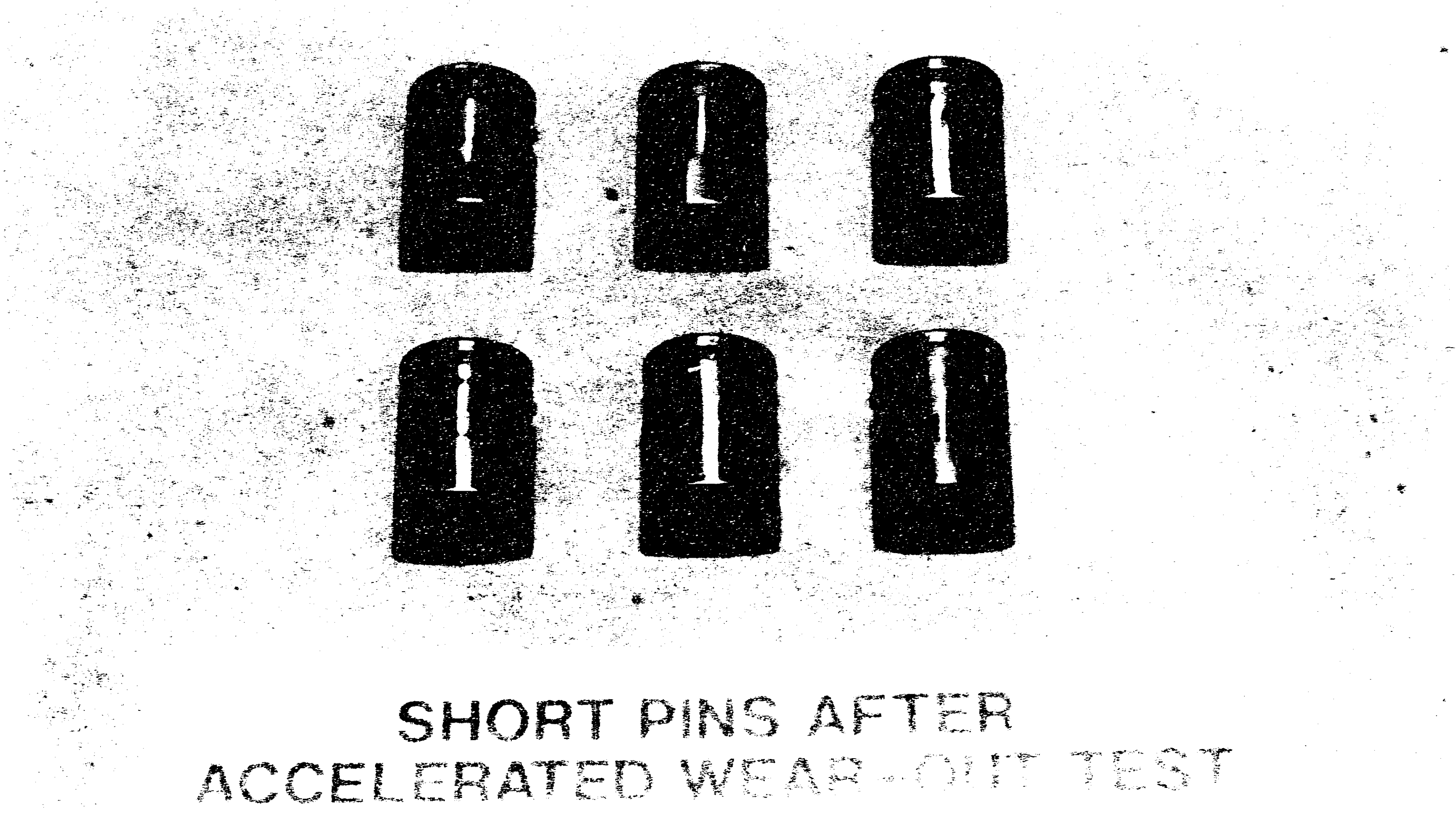


Figure 16: Pins from the Narrow Rollers that Successfully Completed the Accelerated Wear-Out Test

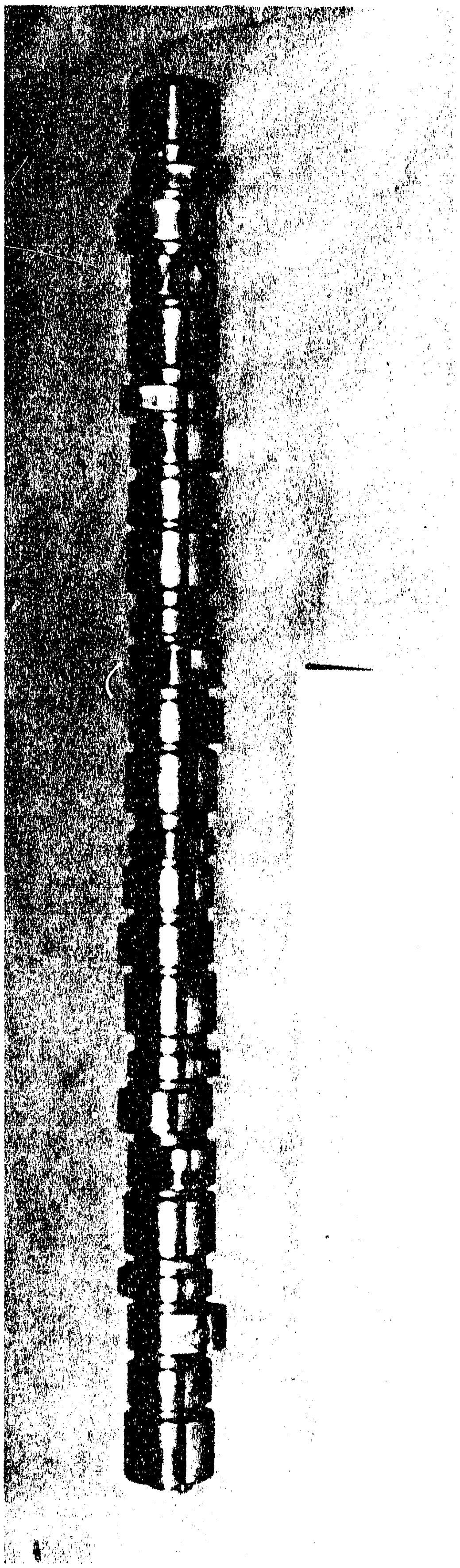
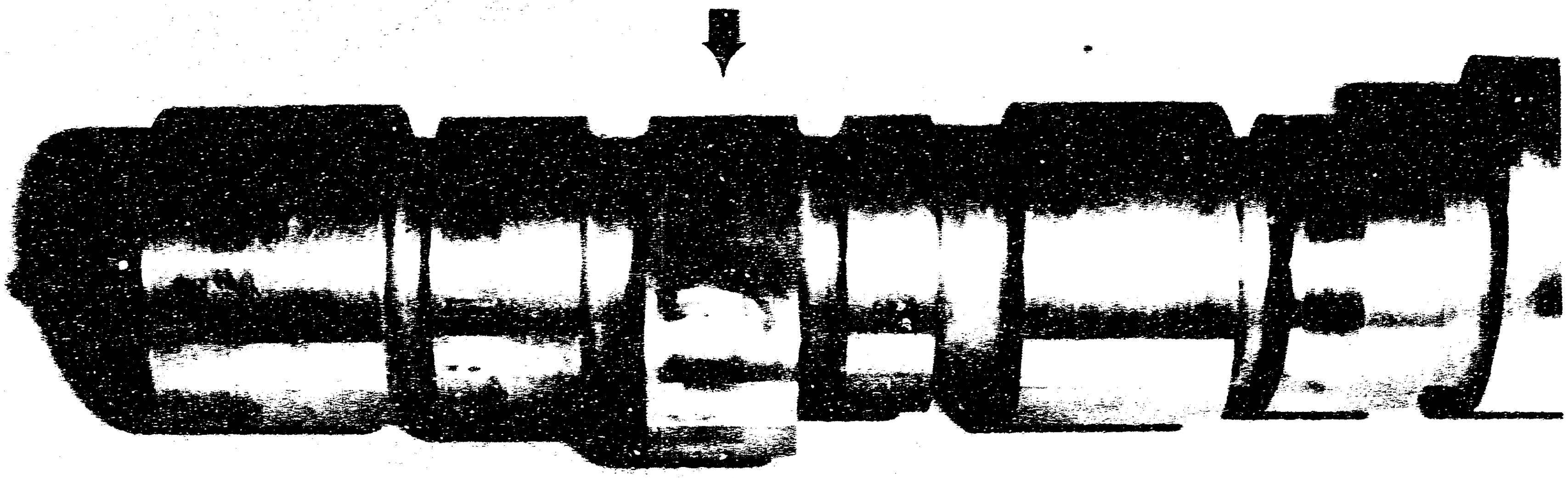


Figure 17: Series 60 Camshaft after Accelerated Wear-Out Test



SERIES 60 CAMSHAFT

AFTER ACCELERATED WEAR-OUT TEST
WITH DOMESTIC CERAMIC ROLLERS

POSITION # 1

Figure 18: Injector Lobe of the Series 60 Camshaft Under Wide Roller after Accelerated Wear-Out Test

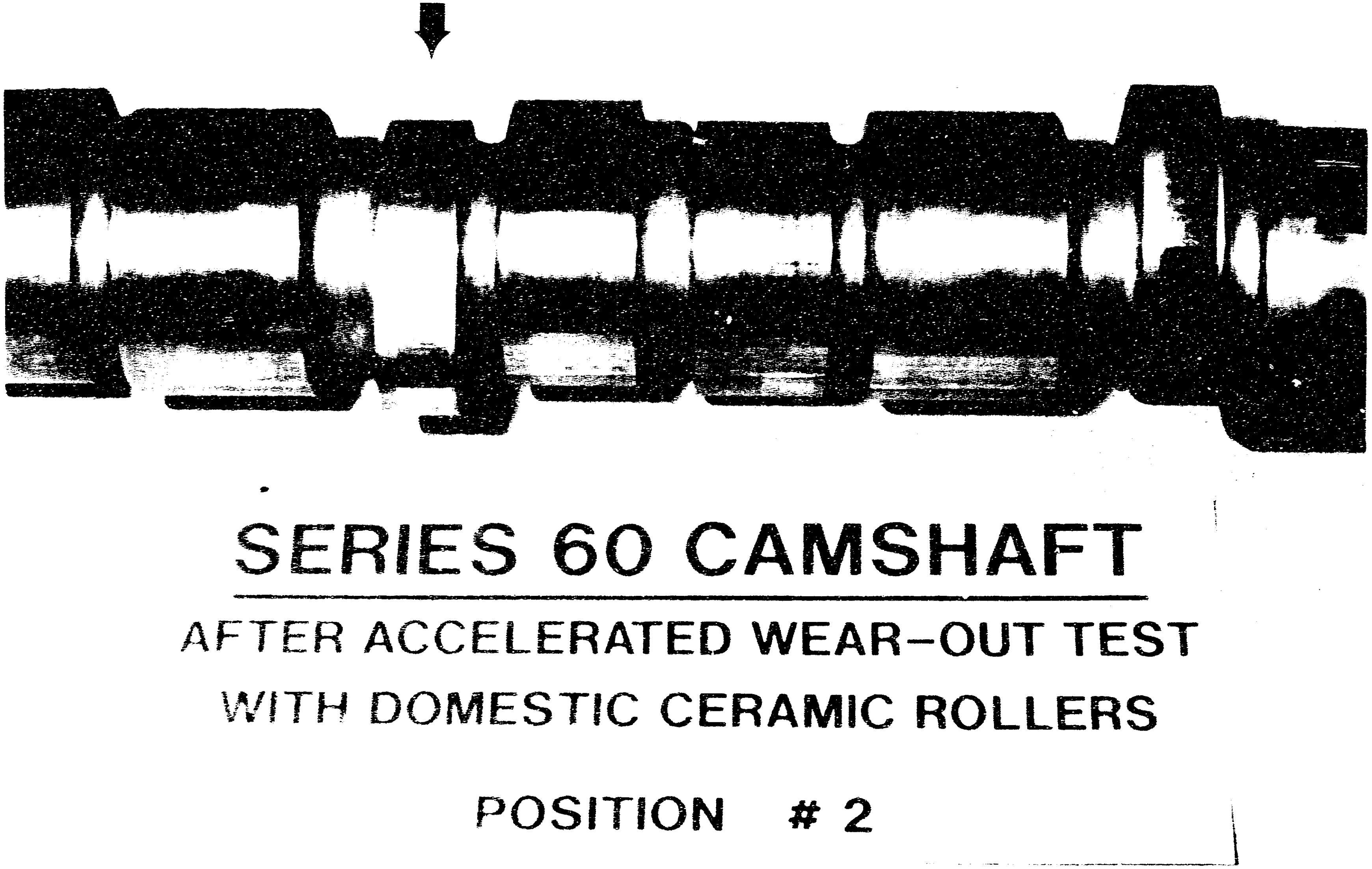


Figure 19: Intake Lobe of the Series 60 Camshaft Under Narrow Roller after Accelerated Wear-Out Test

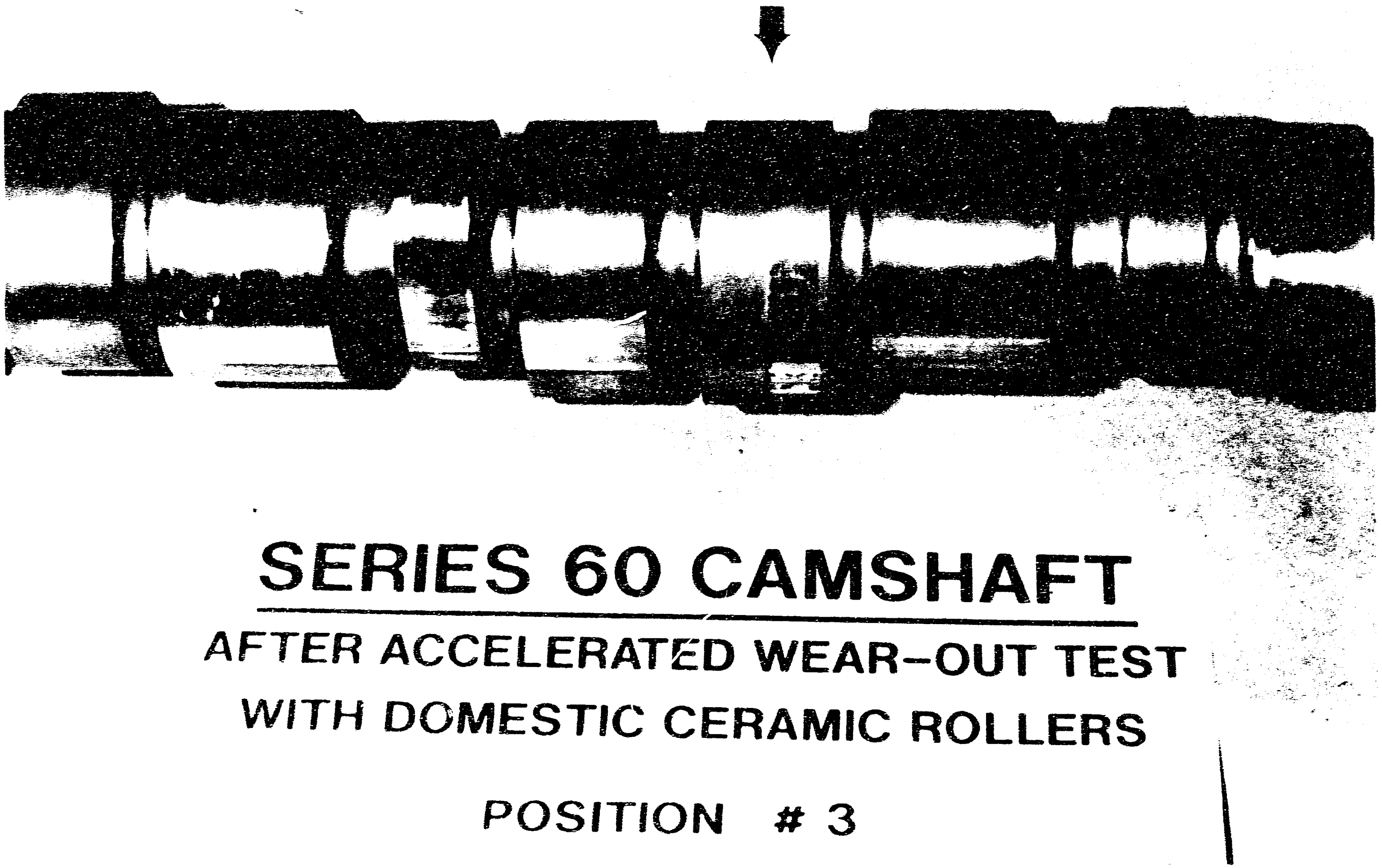


Figure 20: Exhaust Lobe of the Series 60 Camshaft Under Narrow Roller after Accelerated Wear-Out Test

SERIES 60 CAMSHAFT

AFTER ACCELERATED WEAR–OUT TEST

WITH DOMESTIC CERAMIC ROLLERS

POSITION # 4

Figure 21: Exhaust Lobe of the Series 60 Camshaft Under Wide Roller after Accelerated Wear-Out Test

#	Pos. on rig	Before the test		After the test		Pin/rol. clear. change	Roller weight change	Pin diam. change	ID wear	Cam wear
		Roller weight	Pin/rol. clear.	Pin/rol. clear.	Roller weight					
NARROW ROLLERS										
56	I1	30.8934	.0016	.0016	30.8938	0	.0004	-.00003	-.00003	.0010
57	I2	30.9368	.0017	.0019	30.9376	.0002	.0008	-.00001	.00019	.0017
58	I3	30.8837	.0012	.0018	30.8830	.0006	-.0007	-.00004	.00056	.0016
60	I4	32.2002	.0013	.0018	32.2032	.0005	.0030	0	.00050	.0009
62	I5	32.1834	.0017	.0020	32.1836	.0003	.0002	-.00001	.00029	.0010
64	I6	32.1517	.0016	.0017	32.1513	.0001	-.0004	-.00002	.00008	.0005
69 *	E1	31.7133	.0014	.0018	31.3776	.0004	-.3357	.00004	.00044	.0030
74	E2	31.2852	.0017	.0019	31.2840	.0002	-.0012	-.00006	.00014	.0009
77 **	E3	31.1443	.0015	.0020	31.1416	.0005	-.0027	-.00004	.00046	.0021

* - failed after 7 cycles
** - failed after 1 cycle

#	Pos. on rig	Before the test		After the test		Pin/rol. clear. change	Roller weight change	Pin diam. change	ID wear	Cam wear
		Roller weight	Pin/rol. clear.	Pin/rol. clear.	Roller weight					
WIDE ROLLERS										
8	J1	62.3569	.0019	.0019	62.3586	0	.0017	.00002	.00002	0
55	J2	62.3288	.0017	.0020	62.3333	.0003	.0045	0	.00030	-.0001
19	J3	62.3023	.0018	.0018	62.3016	0	-.0007	0	0	0
85	J4	62.2040	.0017	.0020	62.2045	.0003	.0005	0	.00030	-.0001
93	J5	62.1786	.0015	.0020	62.1789	.0005	.0003	0	.00050	0
140	J6	62.1920	.0016	.0019	62.1917	.0003	-.0003	0	.00030	0
47	E4	62.2529	.0015	.0018	62.2528	.0003	-.0001	-.00008	.00022	0
90A	E5	62.2227	.0018	.0018	62.2251	0	.0024	-.00005	-.00005	0
92	E6	62.2924	.0014	.0016	62.2921	.0002	-.0003	-.00003	.00017	0

All dimensions are in inches, weights in gramms

Figure 22. Domestic ceramic roller accelerated wear-out test results

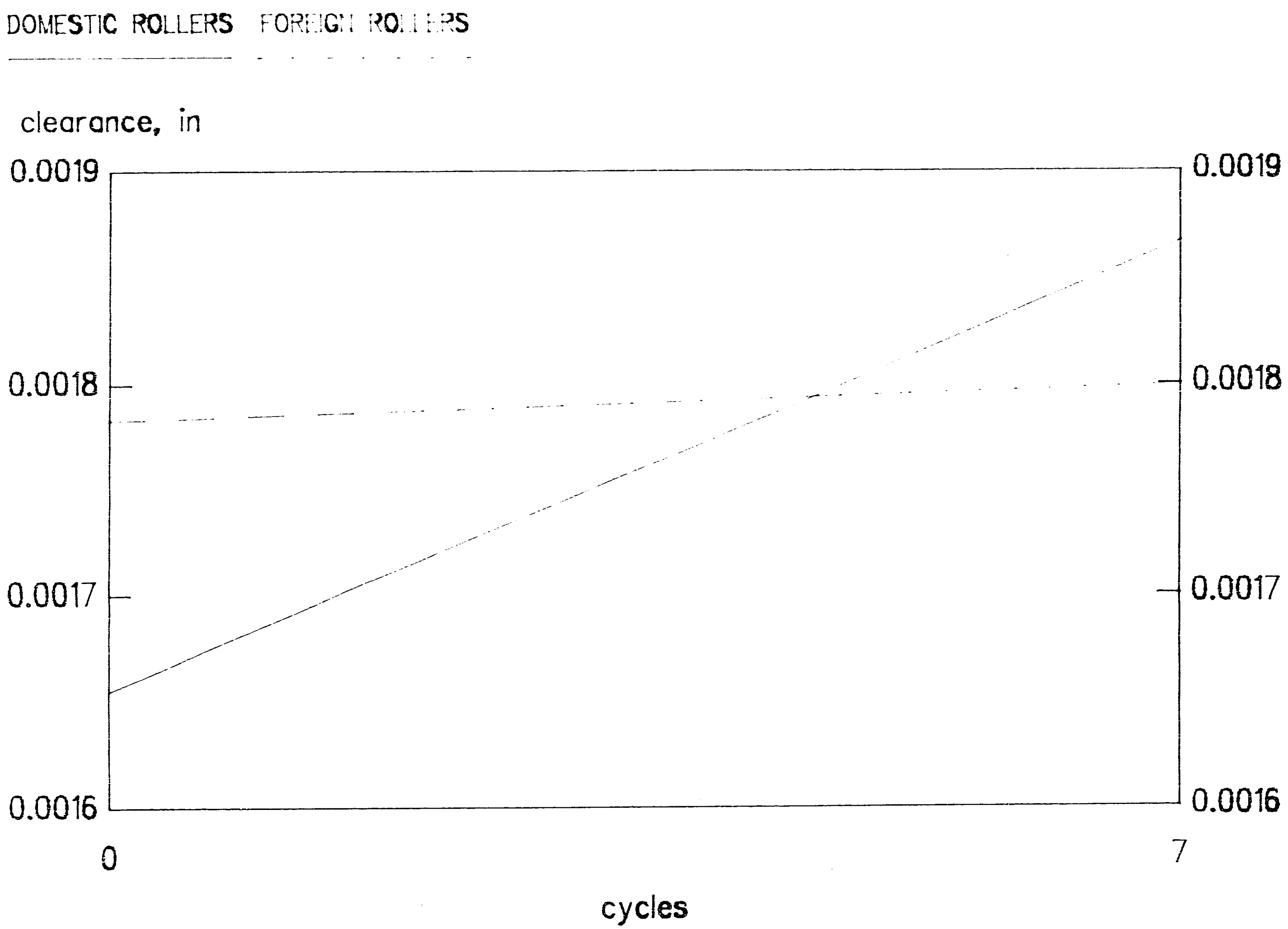


Figure 23: Pin/Roller Clearance Comparison for Wide Rollers

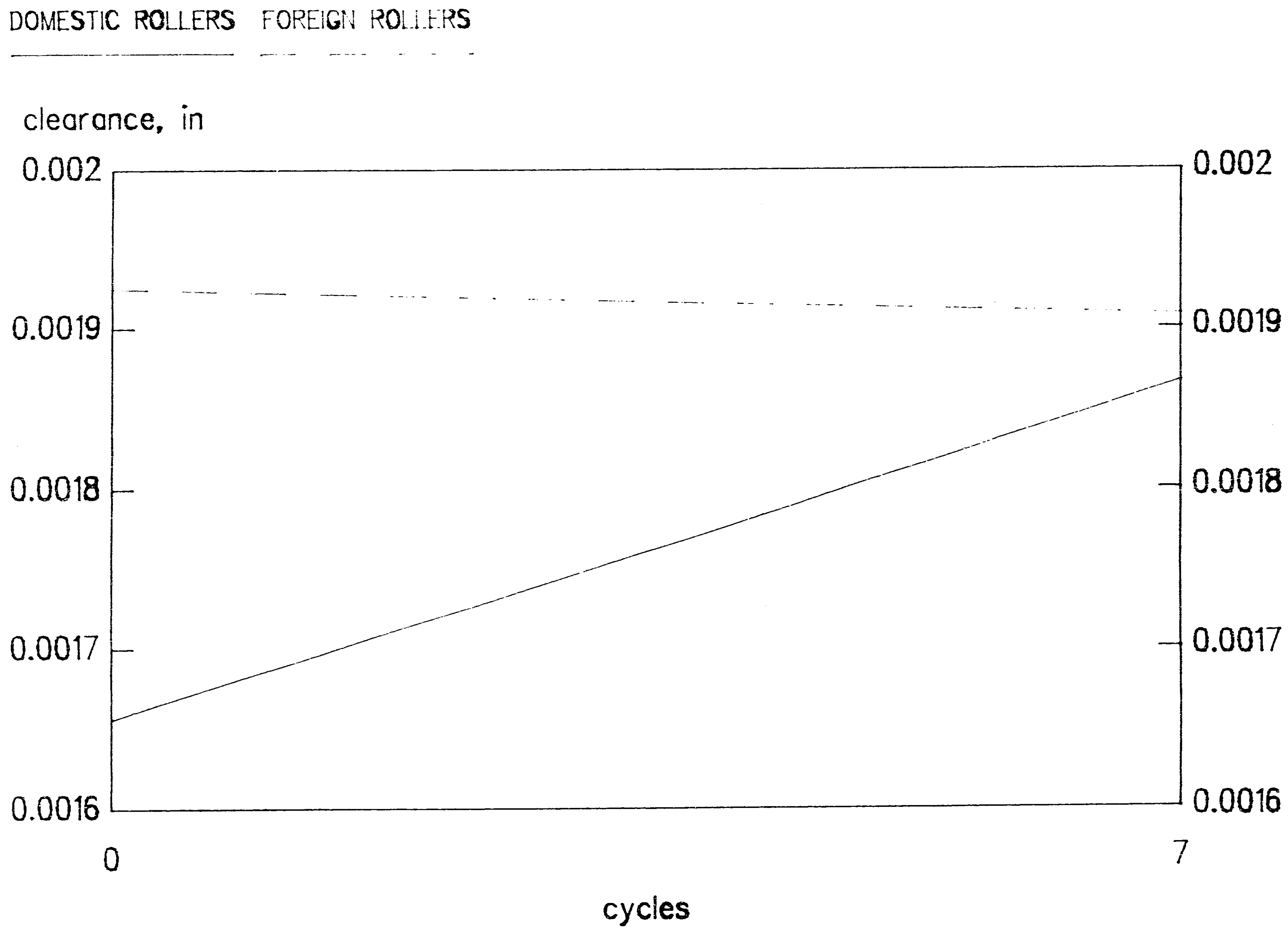
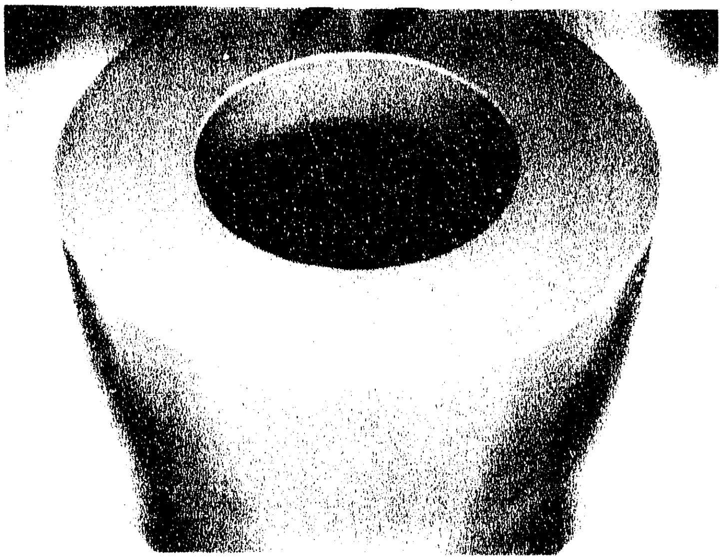
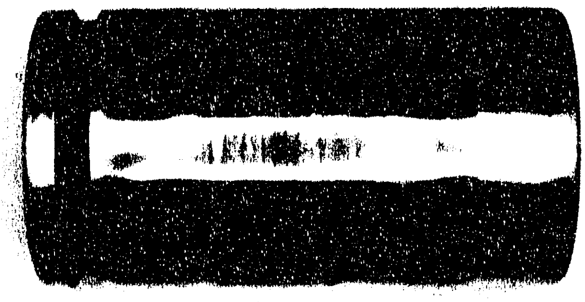


Figure 24: Pin/Roller Clearance Comparison for Narrow Rollers

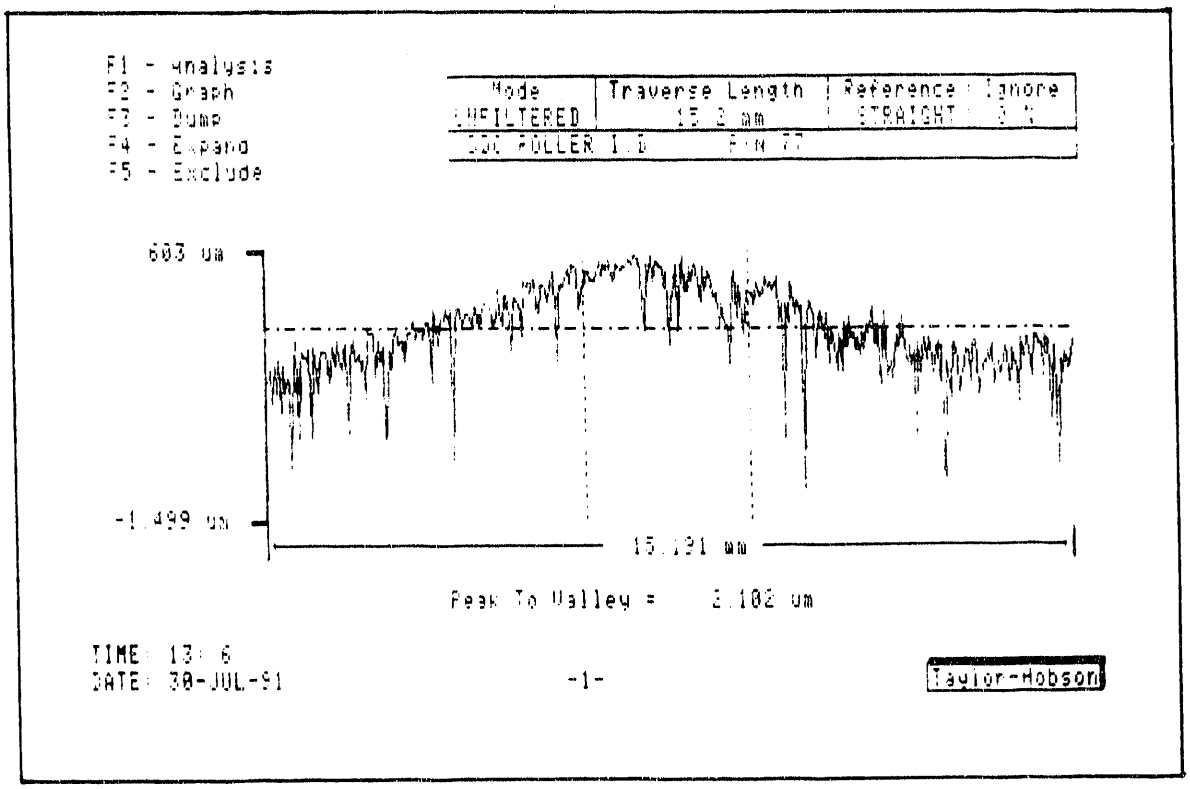


A ID Wear



B Pin Wear

Figure 25: Wide Roller #77 Wear

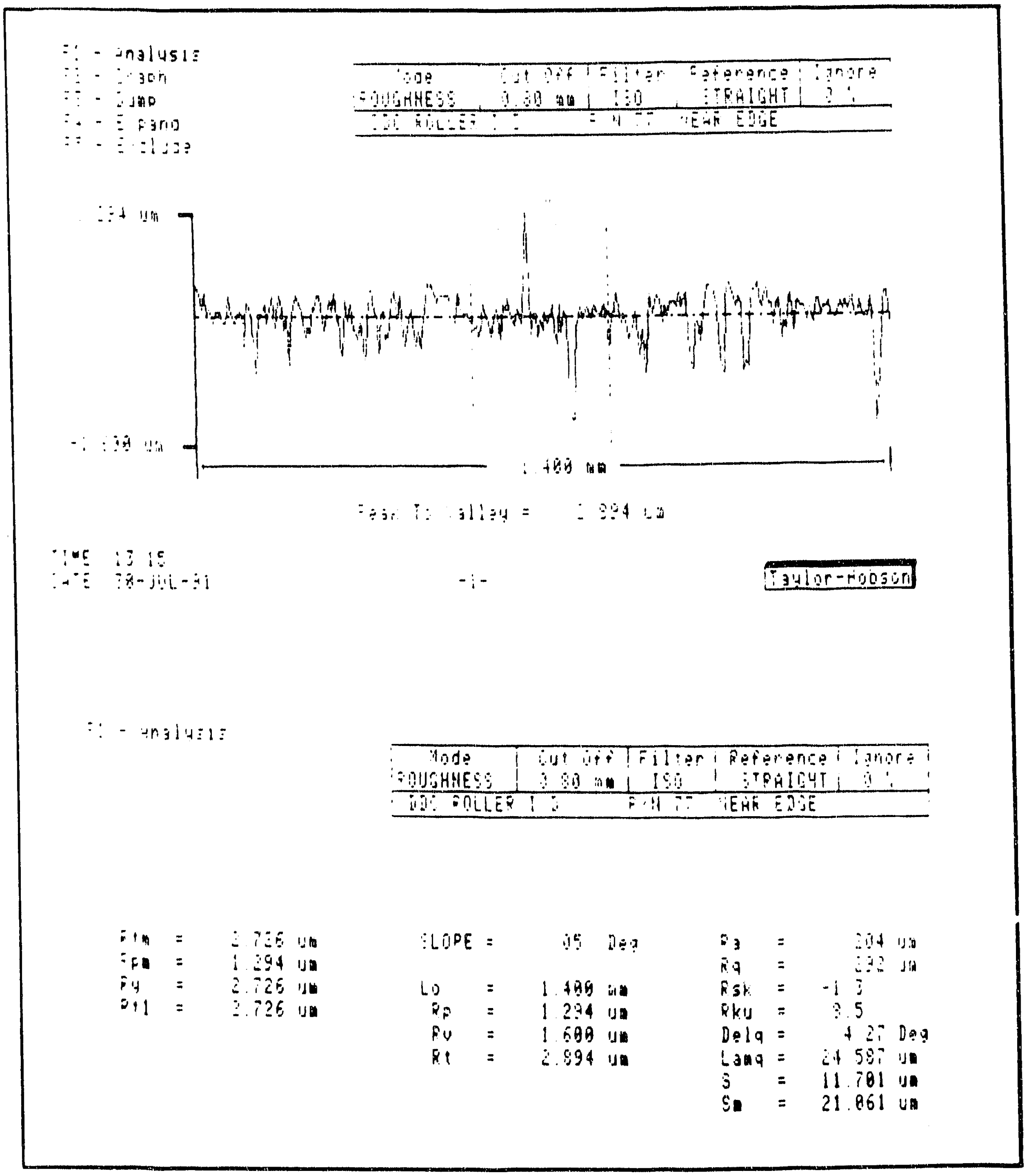


Mode	Traverse Length	Reference	Ignore
UNFILTERED	15.2 mm	STRAIGHT	0 %
[illegible] ROLLER I.D	R/N 77		

Peak To Valley = 2.102 um

TIME: 13: 6
DATE: 30-JUL-91

Figure 26: ID Surface Trace on the Wide Roller #77



F1 - Analysis
F2 - Graph
F3 - Dump
F4 - Expand
F5 - Exclude

Mode	Cut Off	Filter	Reference	Ignore
ROUGHNESS	0.80 mm	ISO	STRAIGHT	0 %
IDC ROLLER I.D.		R/N 77	NEAR EDGE	

Peak To Valley = 2.894 um

TIME 13:15
DATE 28-JUL-91

-1-

Taylor-Hobson

F1 - Analysis

Mode	Cut Off	Filter	Reference	Ignore
ROUGHNESS	0.80 mm	ISO	STRAIGHT	0 %
IDC ROLLER I.D.		R/N 77	NEAR EDGE	

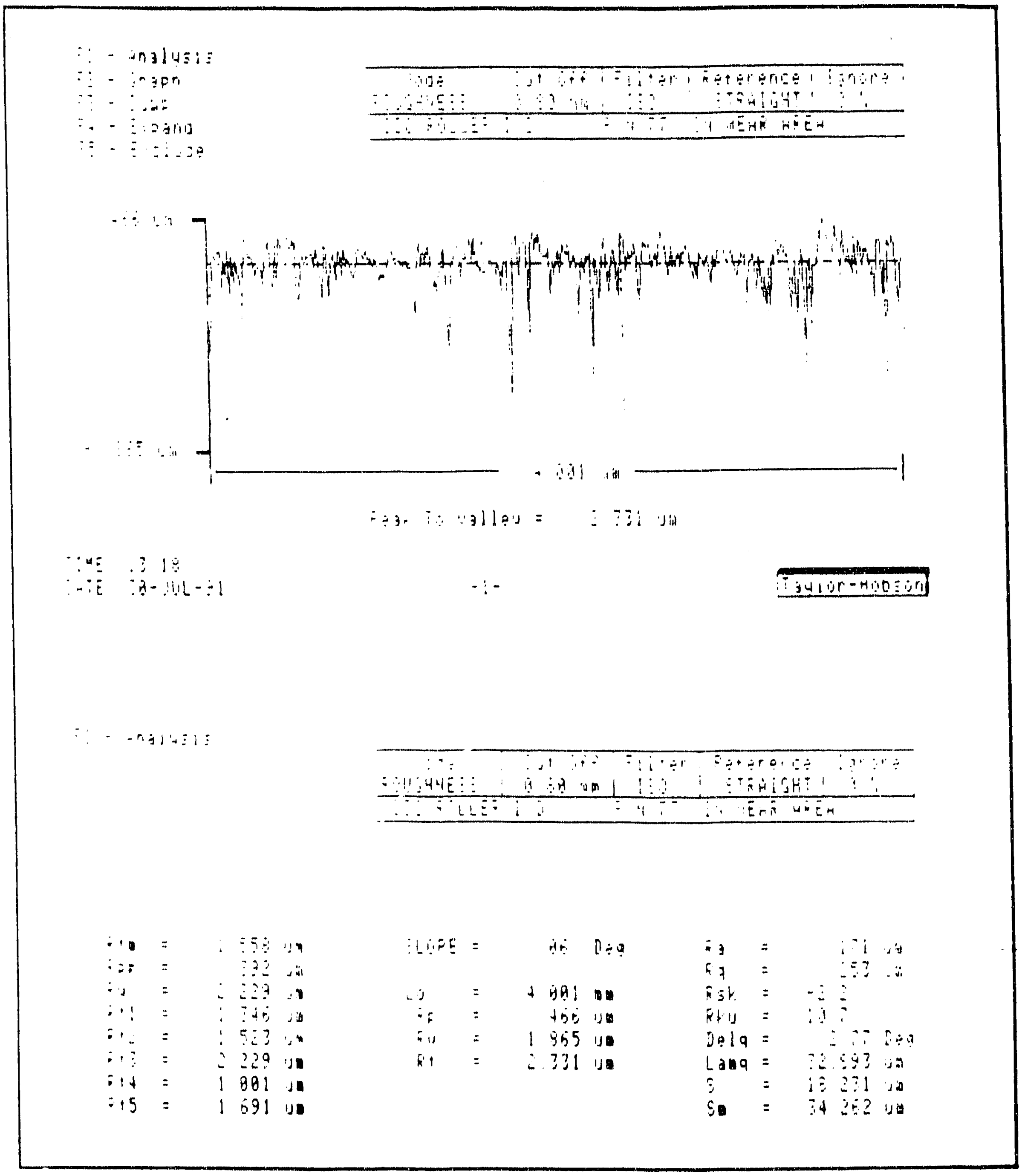
Rtm = 2.736 um
Rpm = 1.294 um
Ry = 2.726 um
Rt1 = 2.726 um

SLOPE = .05 Deg

Lo = 1.400 mm
Rp = 1.294 um
Rv = 1.600 um
Rt = 2.894 um

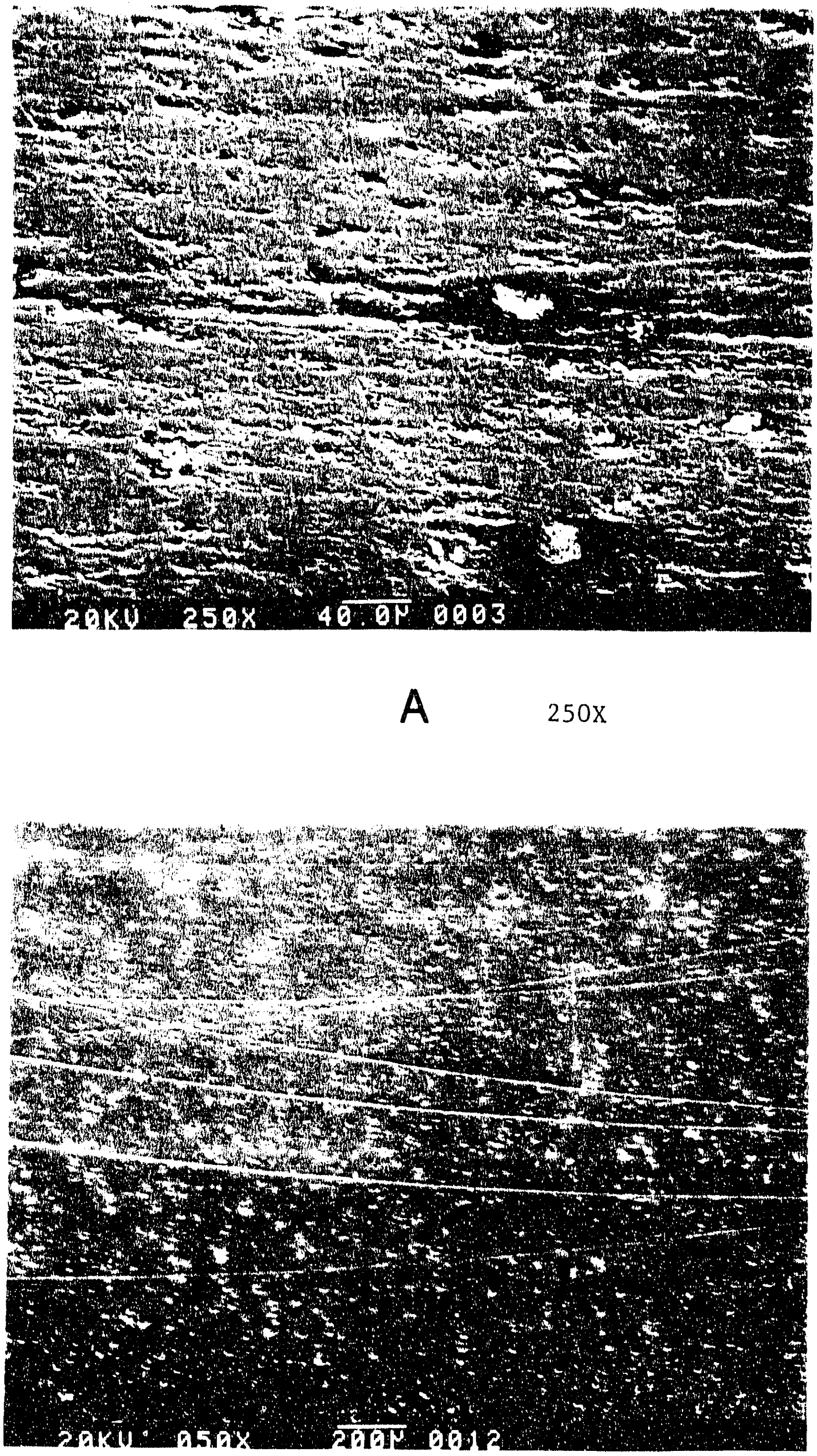
Ra = .204 um
Rq = .292 um
Rsk = -1.3
Rku = 9.5
Delq = 4.27 Deg
Lamq = 24.587 um
S = 11.701 um
Sm = 21.061 um

Figure 27: ID Surface Finish Near Edge of the Wide Roller #77



```
F1 - Analysis
F2 - Graph
F3 - Dump
F4 - Expand
F5 - Exclude

    Mode       Cut Off | Filter | Reference | Ignore
ROUGHNESS     0.80 mm  |  2CR   | STRAIGHT  |  0 %
ID ROLLER 1.0          # 4 77   IN WEAR AREA

+15 um
-125 um
                     4.001 mm

              Peak To Valley =    2.731 um

TIME  13 18
DATE  18-JUL-91                 -1-              Taylor-Hobson


F1 - Analysis

    Mode       Cut Off | Filter | Reference | Ignore
ROUGHNESS     0.80 mm  |  2CR   | STRAIGHT  |  0 %
ID ROLLER 1.0          # 4 77   IN WEAR AREA


Rtm  =   1.558 um      SLOPE =    .06  Deg     Ra   =      .171 um
Rpm  =    .332 um                              Rq   =      .253 um
Ry   =   2.229 um      Lo    =  4.001 mm       Rsk  =   -2.2
Rt1  =   1.746 um      Rp    =   .466 um       Rku  =   10.7
Rt2  =   1.523 um      Rv    =  1.965 um       Delq =     2.77 Deg
Rt3  =   2.229 um      Rt    =  2.331 um       Lamq =   72.593 um
Rt4  =   1.801 um                              S    =   18.231 um
Rt5  =   1.691 um                              Sm   =   34.262 um
```

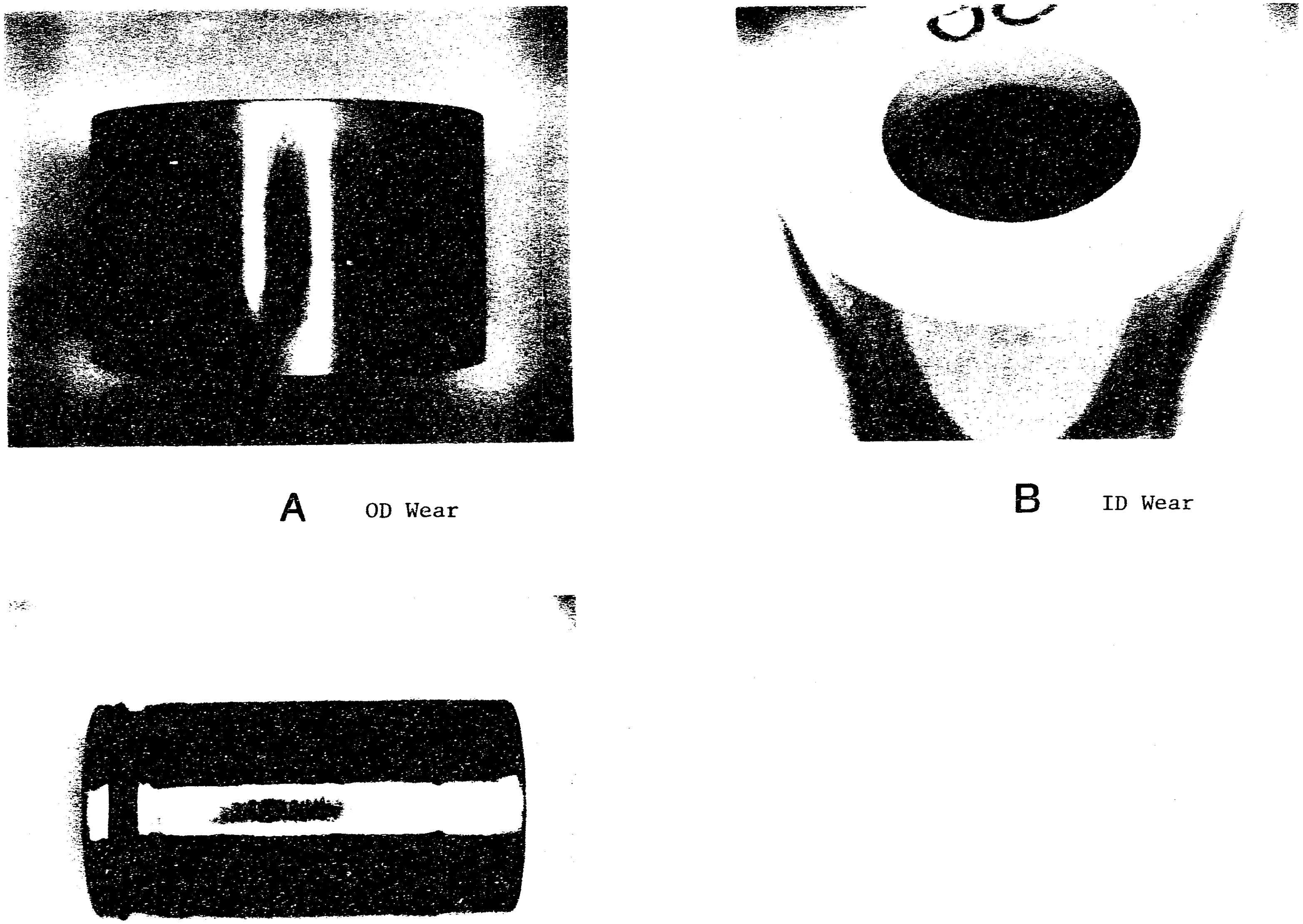
Figure 28: ID Surface Finish Near the Center of the Wide Roller #77



A 250X

B 50X

Figure 29: Photomicrographs of the Wide Roller ID Wear



A OD Wear

B ID Wear

C Pin Wear

Figure 30: Wide Roller #80 Wear

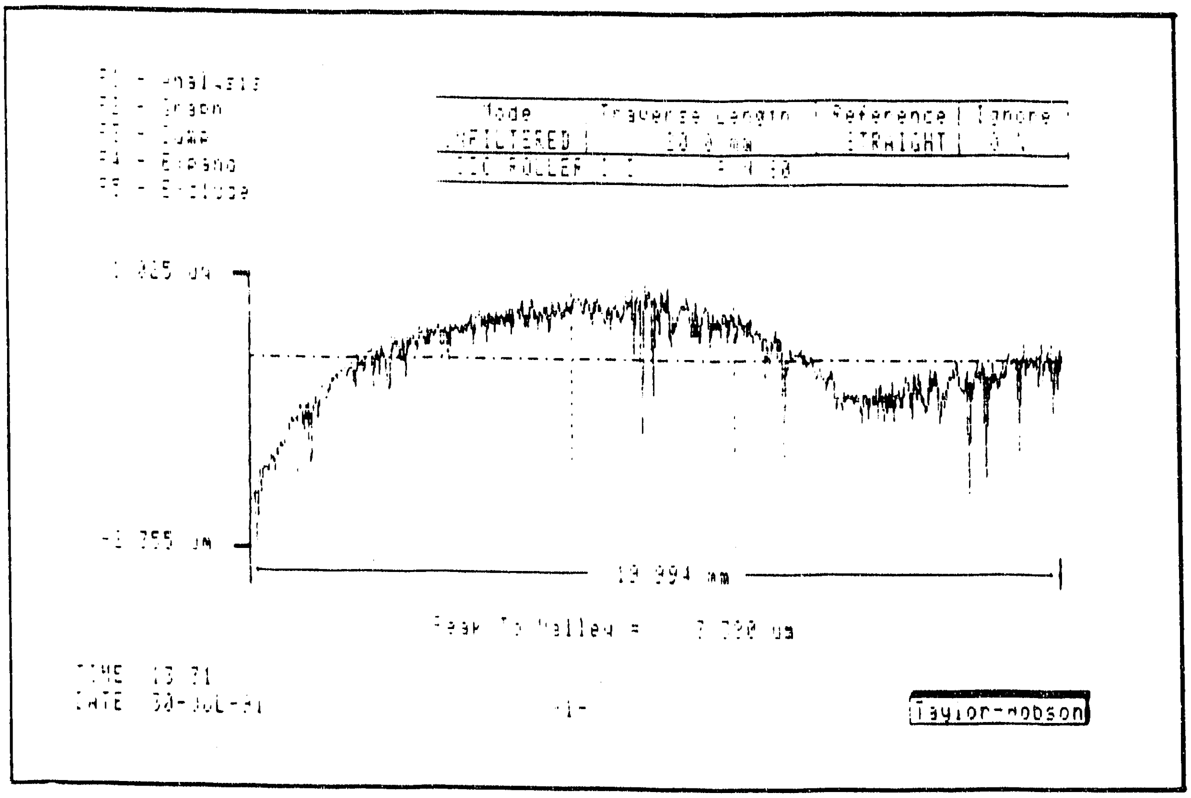
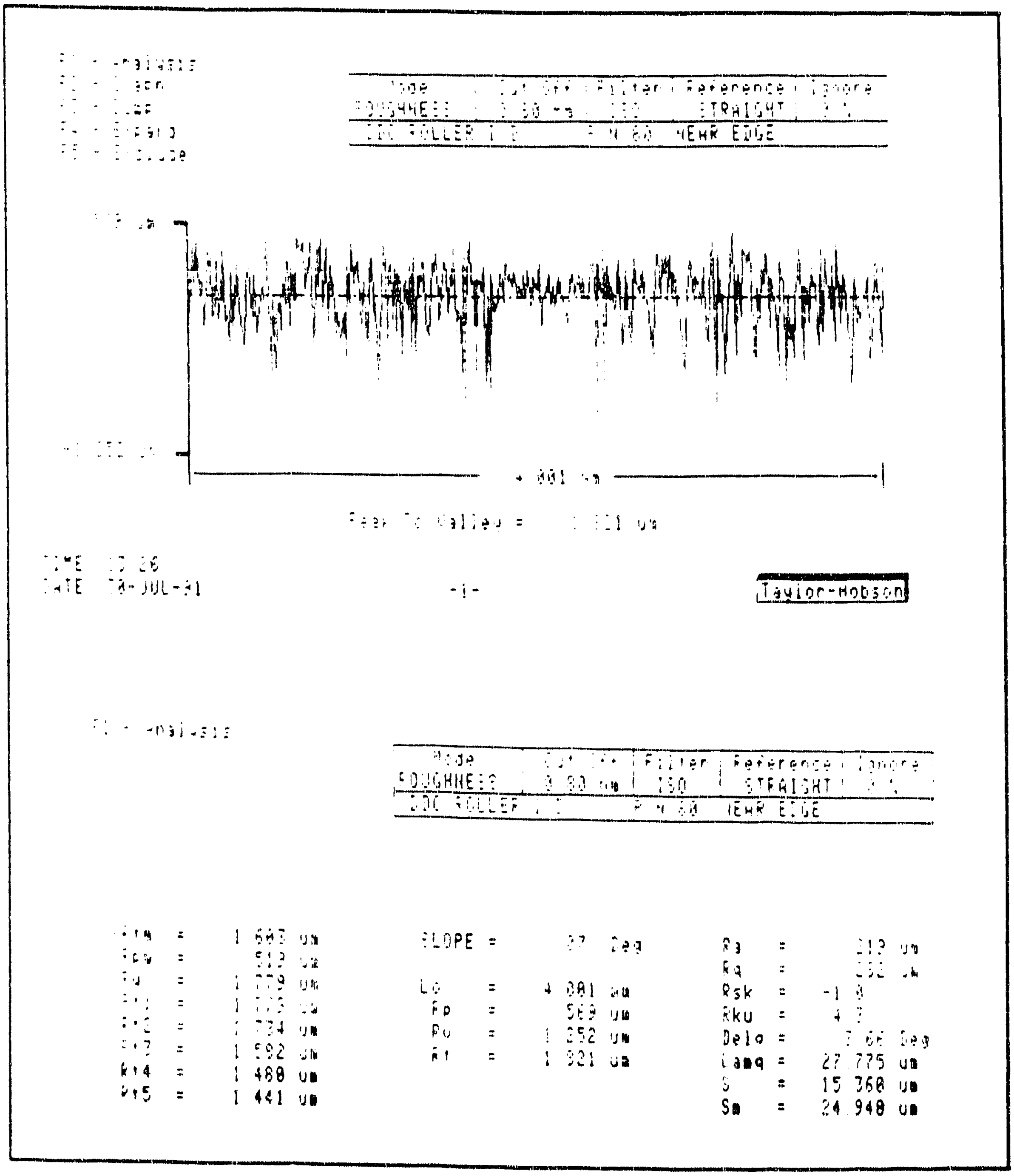


Figure 31: ID Surface Trace on the Wide Roller #80



F1 - Analysis
F2 - Scan
F3 - Zoom
F4 - Expand
F5 - Include

Mode	Cut Off	Filter	Reference	Ignore
ROUGHNESS	0 80 mm	2CR	STRAIGHT	0 %
IDC ROLLER 1 2		R N 80	NEAR EDGE	

Peak To Valley = 1 921 um

TIME 10 26
DATE 18-JUL-91

-1-

Taylor-Hobson

F1 - Analysis

Mode	Cut Off	Filter	Reference	Ignore
ROUGHNESS	0 80 mm	2CR	STRAIGHT	0 %
IDC ROLLER 1 2		R N 80	NEAR EDGE	

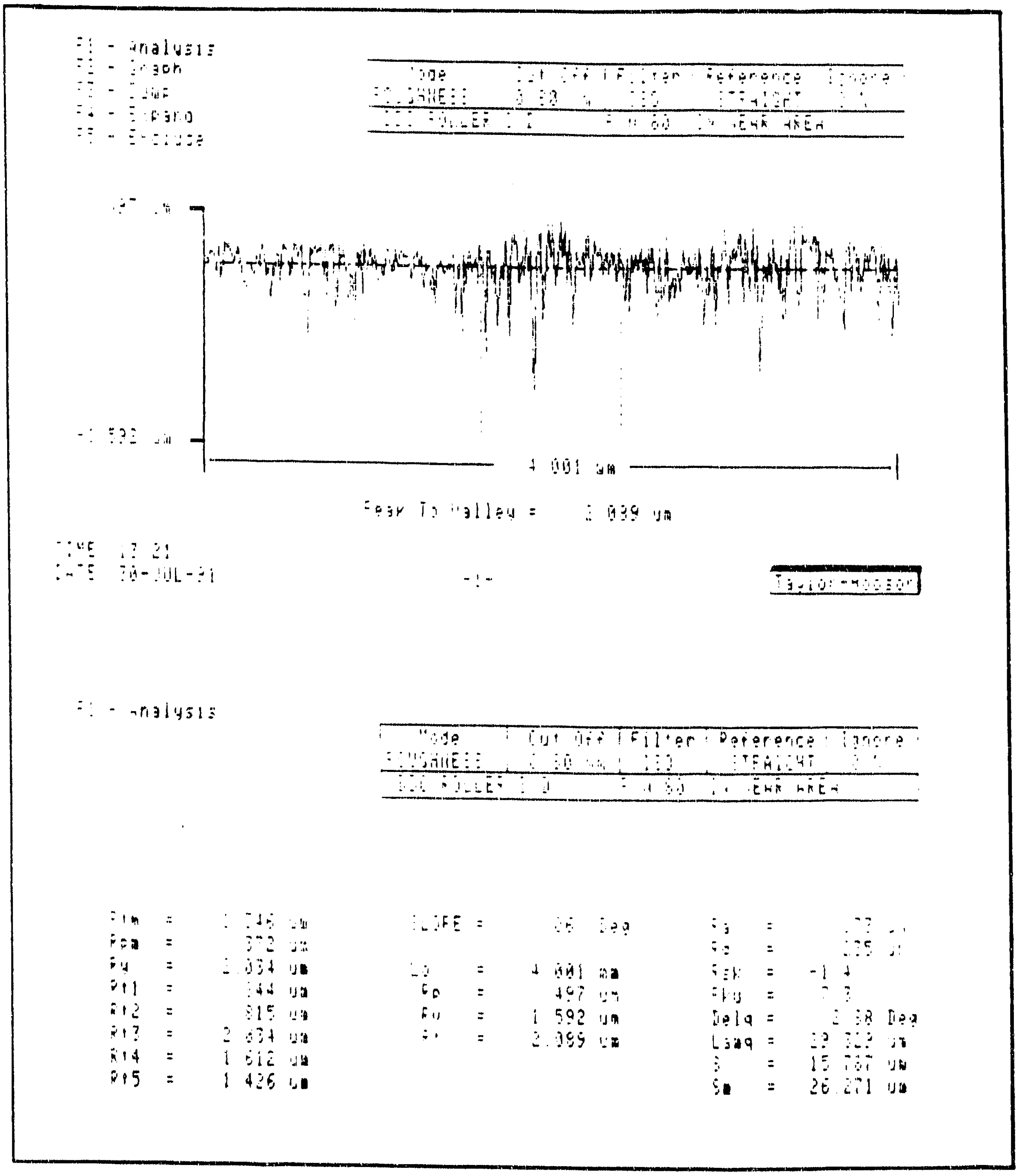
Rtm = 1 603 um
Rpm = 513 um
Ry = 1 779 um
Rt1 = 1 773 um
Rt2 = 1 734 um
Rt3 = 1 592 um
Rt4 = 1 488 um
Rt5 = 1 441 um

SLOPE = 27 Deg

Lo = 4 081 um
Rp = 569 um
Rv = 1 252 um
Rt = 1 921 um

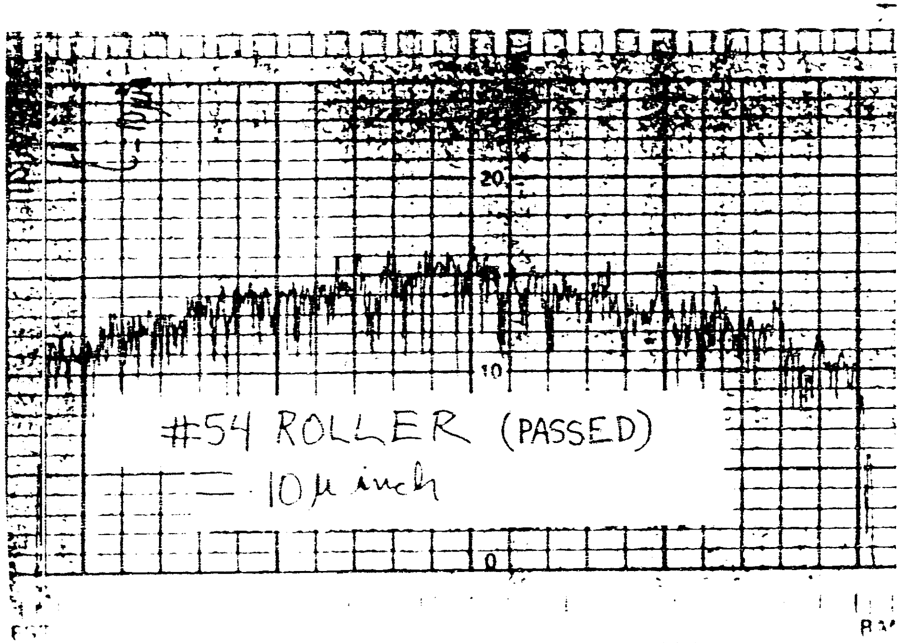
Ra = 213 um
Rq = 292 um
Rsk = -1 0
Rku = 4 3
Delq = 7 66 Deg
Lamq = 27.775 um
S = 15 760 um
Sm = 24.948 um

Figure 32: ID Surface Finish Near Edge of the Wide Roller #80

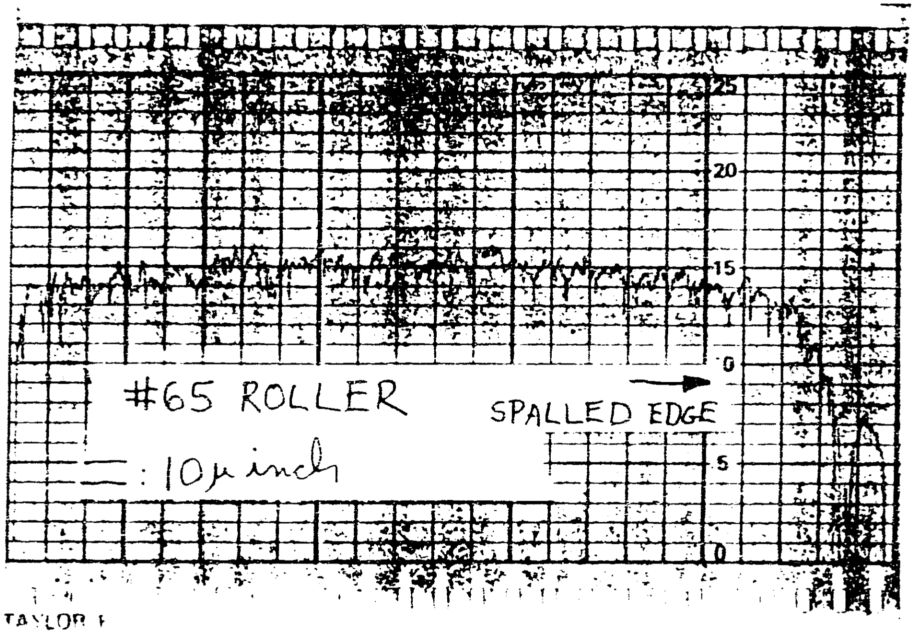


```
F1 - Analysis
F2 - Graph
F3 - Save
F4 - Expand
F5 - Exclude

   Mode       Cut Off  Filter  Reference  Ignore
ROUGHNESS     0.80 mm   2CR    STRAIGHT   [illegible]
ID ROLLER [illegible]     # 80  IN NEAR AREA

.497 um

-1.592 um
                4.001 mm

        Peak To Valley =   2.089 um

TIME  1[illegible] 21
DATE  30-JUL-91                -1-               Taylor-Hobson

F1 - Analysis

   Mode       Cut Off  Filter  Reference  Ignore
ROUGHNESS     0.80 mm   2CR    STRAIGHT   [illegible]
ID ROLLER [illegible]     # 80  IN NEAR AREA

Rtm  =   1.346 um     SLOPE =    .06  Deg     Ra   =     .177 um
Rpm  =    .372 um                             Rq   =     .235 um
Ry   =   2.034 um     Lo    =  4.001 mm       Rsk  =  -1.4
Rt1  =    .844 um     Rp    =   .497 um       Rku  =   7.3
Rt2  =    .815 um     Rv    =  1.592 um       Delq =    2.38 Deg
Rt3  =   2.034 um     Rt    =  2.089 um       Lamq =  29.3[illegible] um
Rt4  =   1.612 um                             S    =  15.787 um
Rt5  =   1.426 um                             Sm   =  26.271 um
```

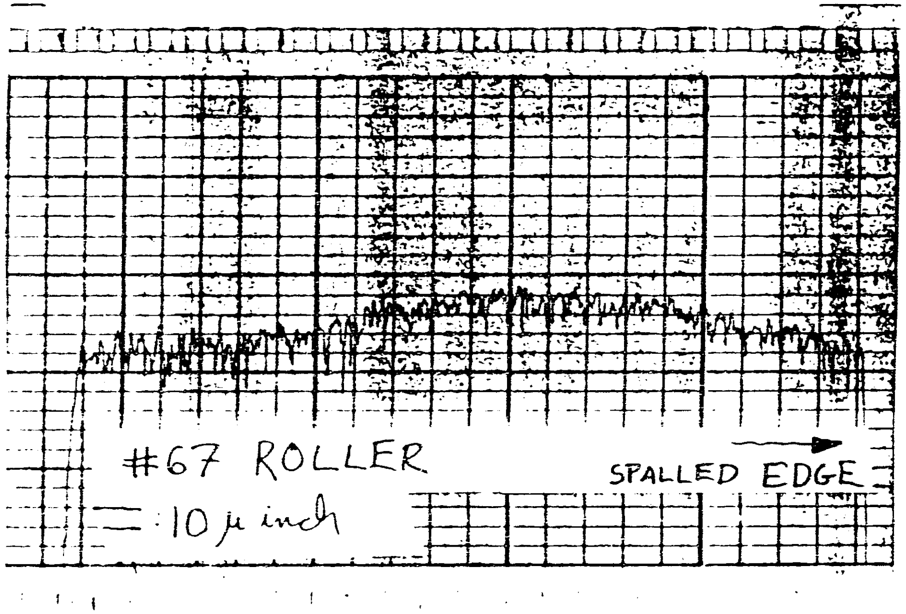
Figure 33: ID Surface Finish Near the Center of the Wide Roller #80



a Roller #54

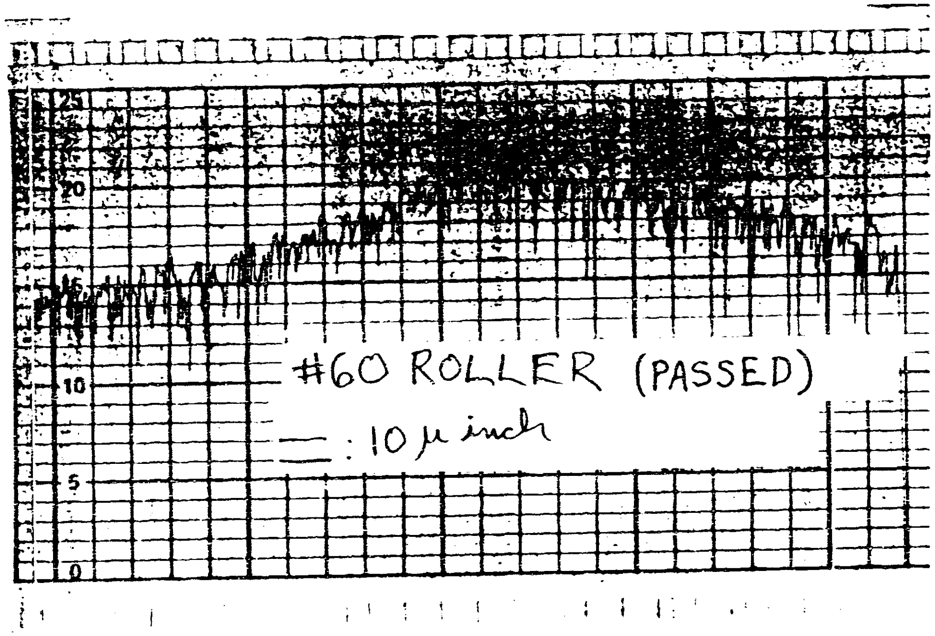


b Roller #65

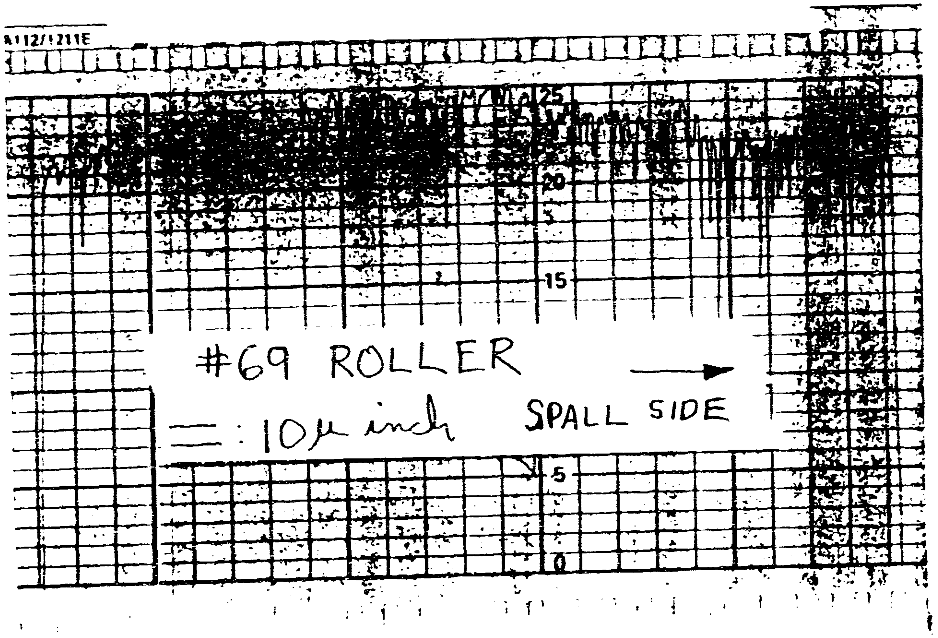


c Roller #67

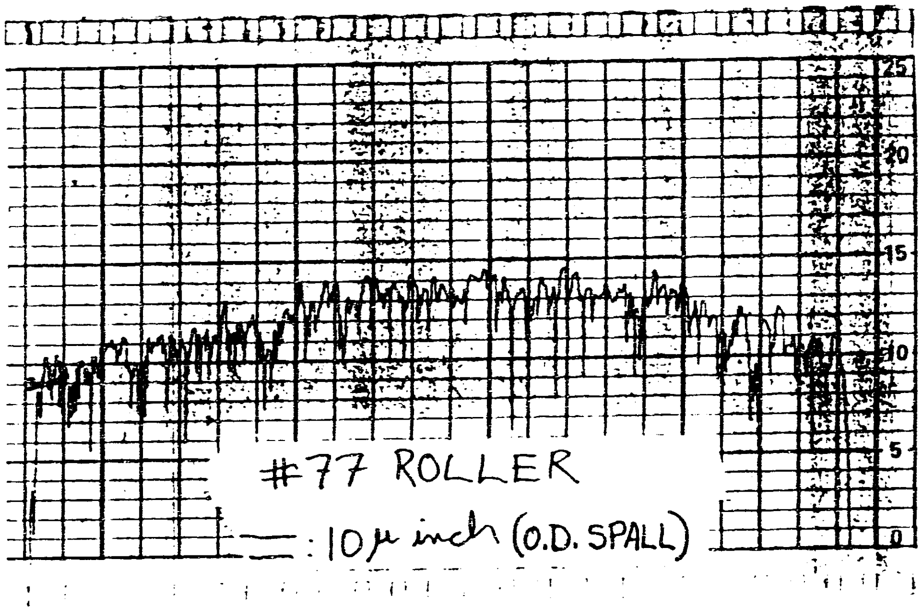
Figure 34: Crown Profiles of the Narrow Rollers After Overspeed Capability Test



a Roller #60



b Roller #69



c Roller #77

Figure 35: Crown Profiles of the Narrow Rollers After Accelerated Wear-Out Test

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