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BDX-613-1007

GRINDING MINIATURE PINION GEARS

October 1973

Bendix Corporation
Kansas City, Missouri

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GRINDING MINIATURE
PINION GEARS

Published October 1973

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Technological Spinoff Report

Contract Number AT(29-1)-613 USAEC

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Bendix Corporation
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GRINDING MINIATURE PINION GEARS

October 1973

Prepared by R. W. Stiles

Although grinding inherently produces a better involute form and finer surface finish than other basic gear fabrication methods, equipment and experience in grinding 120-pitch gears with 0.100 inch pitch diameter were not available when Bendix Kansas City placed a process development contract with the Fellows Company. Bendix had been producing a functional miniature gear by hobbing, but the required surface finish was borderline and burrs on the part were difficult to remove. As a result of this project, a repeatable process was developed for grinding the tooth form and maintaining a 16AA surface finish with minimum burrs. An experimental machine was used in this process development; production equipment is not yet available in U. S. industry for this process but could be developed.

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CONTENTS

Section	Page
SUMMARY	11
DISCUSSION	13
SCOPE AND PURPOSE	13
PRIOR WORK	13
ACTIVITY	14
<u>Setup and Grinding</u>	16
ACCOMPLISHMENTS	16
<u>Cycle Time</u>	16
<u>Inspection Data</u>	19
<u>Deburring</u>	21
APPENDICES	
A. DRAWING AY204473 GRAPHIC GEAR, PINION	25
B. COMPOSITE CHARTS; INVOLUTE PROFILE CHARTS	29
C. WHEEL TURNING MECHANISM	35

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ILLUSTRATIONS

Figure		Page
1	Bendix PN 204473-101 (P-64633)	14
2	Generation of Involute Profiles	15
3	Composite Reading on Fellows Number 4 Redliner Gear Checker.	19
4	Profile Recording on Fellows 12-M Involute Machine	20
5	Photographs of Tooth Profile at 200X (P-74711)	22
6	Comparison of Burrs Produced by Grinding and Hobbing (P-74710)	23
A-1	Pinion Gear Blank	27
A-2	Graphic Gear, Pinion	28
B-1	Master Gear and Staging Fixture for Redliner Gear Checker (P-64636)	31
B-2	Composite Readings Obtained at BKC on Fellows Number 4 Redliner Gear Checker	32
B-3	Typical Involute Profile Recorded on Fellows 12-M Involute Machine	33
C-1	Full Form Diamond Dressing Tool	37
C-2	Wheel Truing Attachment (P-64631).	38
C-3	Wheel Truing Device	40
C-4	Photograph of Diamond Dresser and Grinding Wheel (P-64635).	41

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TABLE

Number		Page
1	Inspection Data for Parts Ground in Support of Development Contract.	17

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SUMMARY

Part Number 204473-101 (a 120-pitch, 12-tooth pinion gear) is one of a family of similar gears used in small escapement assemblies. The timing repeatability of the escapement assemblies is influenced by the accuracy and surface finish on the gearing. Consequently, this pinion and the other gears in the escapement assemblies require a 16 microinch (AA) surface finish on the working surfaces of the teeth and a tooth form to AGMA quality class 11b+. The blank for the 120 pitch gear is extremely small (0.100 PD) and made from 17-4 PH stainless steel, heat treated to a hardness of Rockwell "C" 41 minimum.

Bendix is producing this gear by hobbing using a Class AAA hob. Although a functional gear is being produced when the hobs are sharp, the required surface finish is borderline and deburring is a significant portion of the fabrication time. The most logical step for improvement of the process then was grinding the tooth form. A process development contract was placed with the Fellows Company (formerly the Fellows Gear Shaper Company) to develop a repeatable process for grinding the tooth form and maintaining a 16 microinch (AA) surface finish with minimum burrs. Fellows was to develop any tooling necessary for an experimental grinder in their shop and produce 50 pinions to print tolerances.

Grinding inherently produces a better involute form, a better tooth-to-tooth error (TTE), a better total composite error (TCE), and finer surface finishes than other basic gear fabrication methods.

Generation grinding using a threaded grinding wheel is especially adaptable to high volume production work. This process operates on the same principle as hobbing, in that the threaded grinding wheel acts like a rack with the lead angle in the thread form allowing continuous action without indexing.

Grinding 120 pitch gears presented no basic problem to the Fellows Company since the experimental machine used in this development project was built to grind fine pitch master gears and shaper cutters. This was the first attempt by anyone, however, to grind a gear with a 0.100 inch pitch diameter.

The endeavor was successful. This was the first time the tooth form on a gear this size had been produced by grinding. One hundred fifty blanks were sent to Fellows to produce the required fifty. Ninety-one gears were ground during this project; 61 were dimensionally acceptable and 30 were not. Out of the 30 unacceptable parts, 15 were lost during setup.

The actual machining time required to grind the tooth form was 5.6 minutes, as compared to 2.4 minutes for hobbing. Production calculations indicated, however, that the grinding time could be reduced 40 percent below that used in the development of this process by increasing the feed rates.

Of the 50 good parts required by contract, 74 percent fell within a range of 0.0002 to 0.0004 inch on the TCE, with only 12 percent exceeding 0.0004 inch. Seventy-six percent of the 50 parts were within a spread of +0.0002 -0.0003 inch from nominal on the over pin measurement of the pitch diameter.

Three approaches were taken to qualify the surface finish produced: five good parts were checked on an involute checking machine at Fellows' plant using 5000 to 1 amplification; five good parts were visually compared to a known standard by Bendix inspection personnel for a visual interpretation of surface finish; and three ground and three hobbled gears were photographed on a scanning electron microscope to compare the surface finish at high magnification.

All of the techniques used indicated that better than a 16AA surface finish was obtained.

A sample of ten ground gears was vibratory deburred for one hour in N8 media (fused Al_2O_3) and PC-12B burnishing compound. All of the grinding burrs were removed from the parts with no apparent damage to the surface finish when examined under 25X magnification.

Although a process was developed by the Bendix Kansas City Division and the Fellows Company to grind miniature pinion gears, production equipment with this capability is not available. Prior to this project Bendix made a through search of the machine tool industries in both the United States and Europe for a gear grinder capable of producing this pinion gear. The response was negative and no interest could be generated because of the limited marketing potential for such a machine. The grinder Fellows used in this project was an experimental machine built for their internal use. The lack of refinement in this machine limited its application to production use.

All tests performed on the escapement units have shown that functional gears are being produced by hobbing. For this reason, and because production grinding equipment for this size and type of gear is not presently available, changing the fabrication process is not warranted at this time. However, the development of the grinding process has made the parameters available for use in the design and fabrication of a production machine if the future need arises.

DISCUSSION

SCOPE AND PURPOSE

Part Number (PN) 204473-101 (a 120-pitch, 12-tooth pinion gear) is one of a family of similar gears used in escapement assemblies. The timing repeatability of the escapement assemblies is influenced by the accuracy and surface finish on the gearing. Consequently this pinion and the other gears in the escapement assemblies require a 16 microinch (AA) surface finish on the working surfaces of the teeth and a precision tooth form to AGMA quality class 11b+. Small commercial pinions of this pitch and size are fabricated by hobbing and are generally made of soft material such as brass or mild steel. For this reason little effort had been made by industry to develop grinding equipment for this size gear. The blank for the 120 DP gear is extremely small (0.100 PD) and made from 17-4 PH stainless steel heat treated to a hardness of Rockwell "C" 41 minimum which places it at the upper limits of machinability. Figure 1 shows the relative size of PN 204473-101.

Bendix was producing this gear by hobbing, using a Class AAA hob. Although a functional gear was being produced when the hobs were sharp, the required surface finish was borderline and deburring had become a major problem. Therefore the most logical step for improvement of the process was to grind the tooth form. A process development contract was placed with the Fellows Company (formerly the Fellows Gear Shaper Company) to develop a repeatable process for grinding the tooth form and maintaining a 16 microinch (AA) surface finish with minimum burrs. Fellows was to develop any tooling necessary for an experimental grinder in their shop and produce 50 pinions to print tolerances.

PRIOR WORK

Gear grinding is one of the earliest methods used to finish gears.¹ Grinding inherently produces a better involute form, a better tooth-to-tooth error (TTE), a better total composite error (TCE), and finer surface finishes than other basic gear fabrication methods. Gear grinding is used when the need for any of all of the above conditions exist. As the material in a blank becomes harder, grinding may be the only method available to produce the gear teeth form. Although grinding can be performed at any

¹Tool Engineers Handbook, 2nd Edition, American Society of Tool and Manufacturing Engineers, McGraw-Hill, 1959, pp. 44-87.

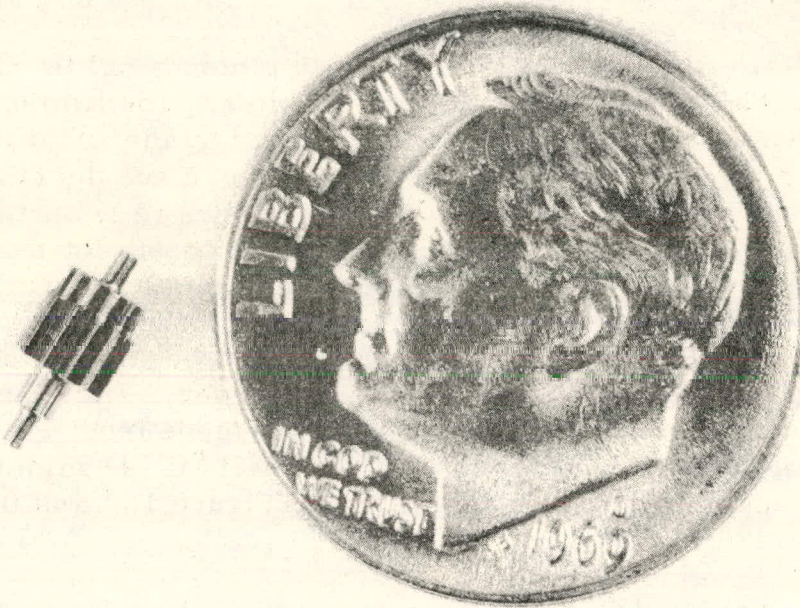


Figure 1. Bendix PN 204473-101

hardness range, optimum grindability is from RC 40 to RC 55.² Coarse pitch gears (up to 48 DP) require prefinishing operations, such as hobbing or shaping preparatory to grinding, but fine pitch gears (48 DP and finer) are ground from solid blanks.

Generation grinding (Figure 2), using a threaded grinding wheel, is especially adaptable to high-volume production work. This process operates on the same principle as hobbing in that the threaded grinding wheel acts like a rack with the lead in the thread form allowing continuous grinding action without indexing.

ACTIVITY

Grinding 120-pitch gears presented no problem to the Fellows Company since they grind master gears and shaper cutters of this pitch for their

²Michalec, George W., Precision Gearing, Theory and Practice, John Wiley & Sons, 1966, p. 481.

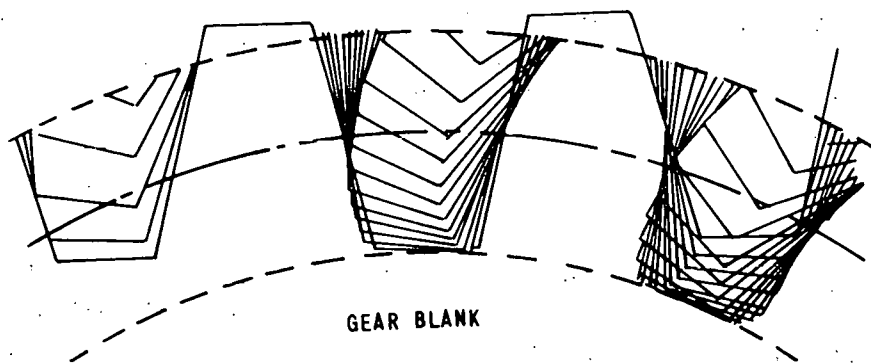


Figure 2. Generation of Involute Profiles

customers. This was the first attempt by anyone, however, to grind a gear with a 0.100-inch pitch diameter. The part presented unique problems with respect to grinding because of its minute size. The blank had to be located and driven off two 0.0261-inch-diameter journals. The proportion of the grinding wheel diameter to the part diameter created problems in the design and fabrication of the workholding centers. To grind to full depth with the wheel, the outside diameter on the workholding centers had to be thinned to 0.075-inch diameter for 1/4-inch length; there was also an apparent danger that both the centers and the work piece might spring away from the grinding wheel due to grinding pressure. Further complicating this operation was the difficulty of applying sufficient holding pressure from the machine's tailstock to drive the gear during the machining cycle.

The machine used in this project was an experimental fine pitch gear grinder. The grinding wheel selected (Norton 38A400-J9VG) was 400-grit aluminum oxide. The diameter of the wheel is 4 inches. A rack form (2 times the pressure angle, or 40°) was threaded into the wheel at a precalculated lead angle (see Appendix C for description of wheel truing and dressing operation). The workholding device was mounted in two female centers; the device consists of a driving center mounted in the headstock and a driven center mounted in the tailstock. The gear blank was placed in the female centers and pressure was applied from the tailstock to keep the blank from rotating during grinding. The work holding centers were horizontally mounted on the machine and the grinding wheel spindle was mounted vertically. While the work spindle rotates the grinding wheel spindle rotates, strokes axially across the part, and feeds in at a controlled amount at the end of each stroke. This action continues until full depth of the gear tooth is reached at which time the wheel head automatically retracts. The lead angle on the grinding wheel allows continuous action without indexing. Only a small portion of the grinding wheel is used at a time. As the wheel dulls the wheel head is shifted vertically (tangential about 0.050 inch) to a new area.

The surface speed was 3769 feet per minute. The workpiece rotated at 300 rpm and the grinding wheel at 3600 rpm. The wheel head slide speed was 0.0029 inch per revolution of the workpiece and the infeed rate was 0.0008 per stroke.

Setup and Grinding

The actual grinding of the pinions from setup to completion took place in a 3-week period. In first setting up the job the originally calculated wheel-head speed of 2 seconds per 0.175 inch stroke was too fast and the wheelhead was feeding in the middle of the stroke. The speed was changed to 9 seconds per stroke which corrected the problem. Drag in the tailstock live center and insufficient drive pressure was hindering the rotation of the pinion gear during the machining cycle. The tailstock center had to be lapped four times before it ran free enough to allow the pinion to rotate with the driving headstock center.

About twenty-five pinions were required to debug the process and tooling. Once the initial setup problems had been corrected, however, little trouble was encountered in grinding the tooth form.

ACCOMPLISHMENTS

A total of 91 gears were ground during the course of this project; 61 were within print tolerance and 30 were scrapped. Of the 30 scrapped parts, 15 were lost during setup. Seventy-four percent of the 50 good parts required by the contract fell within a range of 0.00020 to 0.00040 inch on the TCE with only 12 percent exceeding 0.0004 inch. Seventy-six percent of the 50 parts fell within a range of +0.00020 to -0.00030 inch from the nominal on the over pin measurement of the pitch diameter. See Table 1.

Cycle Time

When the machining time of the grinding operation was compared to hobbing, only the actual machine cycle time was compared since all other functions would have been similar for both methods. The cycle time for hobbing after engaging the machine is 2.4 minutes and the average cycle time established during the course of this project for grinding was 5.6 minutes at the feed rates used. The grinding feed rates used were conservative; by increasing the wheelhead slide speed and the infeed rate, the cycle time could be reduced by as much as 40 percent. To verify this, the last three gears were ground at an infeed rate of 0.0012 inch per stroke. The greater infeed rate had no effect on surface finish, TCE, or pitch diameter.

Table 1. Inspection Data for Parts Ground in Support of Development Contract

Part* Number	TCE** Limit 0.00055 Inch	DOP*** 0.1233 to 0.1219 Inch	Good
1	Did not rotate		
2	Did not rotate		
3	Did not rotate		
4	0.00040	0.12240	X
5	0.00060	0.12190	
6	0.00040	0.12160	
7	0.00040	0.12170	
8	Did not rotate	Did not rotate	
9	0.00035	0.12320	X
10	0.00040	0.12320	X
11	Machine malfunction	Machine malfunction	
12	Ground flat	Ground flat	
13	0.00056	0.12080	
14	0.00015	0.12580	
15	Not checked	0.12400	
16	0.00065	0.12290	
17	Not checked	0.12800	
18	Machine malfunction	Machine malfunction	
19	0.00060	Not checked	
20	0.00035	0.12230	X
21	0.00055	0.12190	X
22	Machine malfunction	Machine malfunction	
23	0.00030	0.12150	
24	0.00055	0.12180	
25	0.00080	0.12280	
26	0.00018	0.12200	X
27	0.00018	0.12260	X
28	0.00045	0.12174	
29	0.00015	0.12250	X
30	0.00050	0.12160	
31	0.00040	0.12280	X
32	0.00020	0.12280	X
33	0.00025	0.12260	X
34	0.00030	0.12260	X
35	0.00040	0.12265	X
36	0.00040	0.12260	X
37	0.00025	0.12250	X
38	0.00028	0.12240	X
39	0.00030	0.12260	X
40	0.00025	0.12250	X
41	0.00040	0.12240	X
42	0.00040	0.12240	X
43	0.00020	0.12260	X
44	0.00015	0.12260	X
45	0.00018	0.12240	X
46	0.00030	0.12250	X

Table 1. Continued. Inspection Data for Parts Ground in Support of Development Contract

Part Number	TCE** Limit 0.00055 Inch	DOP*** 0.1233 to 0.1219 Inch	Good
47	0.00035	0.12190	X
48	0.00045	0.12190	X
49	0.00020	0.12214	X
50	0.00025	0.12234	X
51	0.00030	0.12255	X
52	0.00030	0.12255	X
53	0.00030	0.12260	X
54	0.00025	0.12260	X
55	0.00045	0.12260	X
56	0.00030	0.12267	X
57	0.00020	0.12267	X
58	0.00030	0.12260	X
59	0.00040	0.12260	X
60	0.00025	0.12260	X
61	0.00035	0.12260	X
62	0.00015	0.12260	X
63	No teeth	No teeth	
64	Machine malfunction	Machine malfunction	
65	Machine malfunction	Machine malfunction	
66	0.00025	0.12230	X
67	0.00020	0.12220	X
68	0.00020	0.12200	X
69	Machine malfunction	Machine malfunction	
70	0.00015	0.12240	X
71	0.00050	0.12240	X
72	0.00025	0.12240	X
73	0.00020	0.12300	X
74	0.00040	0.12260	X
75	0.00035	0.12260	X
76	Machine malfunction	Machine malfunction	
77	0.00045	0.12160	
78	0.00035	0.12260	X
79	0.00035	0.12330	X
80	0.00050	0.12342	
81	0.00025	0.12330	X
82	0.00035	0.12260	X
83	0.00035	0.12300	X
84	0.00025	0.12330	X
85	0.00035	0.12260	X
86	0.00040	0.12260	X
87	0.00020	0.12290	X
88	0.00050	0.12290	X
89****	0.00035	0.12160	
90****	0.00030	0.12260	X
91****	0.00040	0.12285	X

*Parts are listed in the order that they were ground.
 **The composite check was made on a No. 4 Fellows Redliner Gear Checker at 800 to 1 amplification.
 ***The over pin measurements were made using 0.015-inch-diameter pins and a super-micrometer.
 ****Ground at an infeed rate of 0.0012 inch per stroke.

Inspection Data

Pitch Diameter and Composite Check

The two basic checks required on the pinion gears consisted of a composite check and a pitch diameter check. The total composite error (TCE) and tooth-to-tooth error (TTE) were checked on a Fellows No. 4 Red Liner at 800 to 1 amplification (Figure 3). The part was held in a special V-block fixture and rolled with a 120 DP, 1.500-inch pitch diameter master gear. The pressure was set at 4 ounces. One of the pinions (Number 7) was selected as a master for both the Red Liner check and pitch diameter check. The No. 7 master pinion and at least two other pinions were checked each day to maintain the sizing on the Red Liner and to ensure that the machine setup was not disturbed during the night shift hours.

The pitch diameter of the pinions was checked over 0.0150-inch-diameter pins on a super-micrometer. The anvil pressure was set at 2 to 2-1/2 ounces. The required pitch diameter limits were 0.1233 to 0.1219 inch. This gave a tooth thickness at the pitch diameter of 0.01399 to 0.01327 inch.

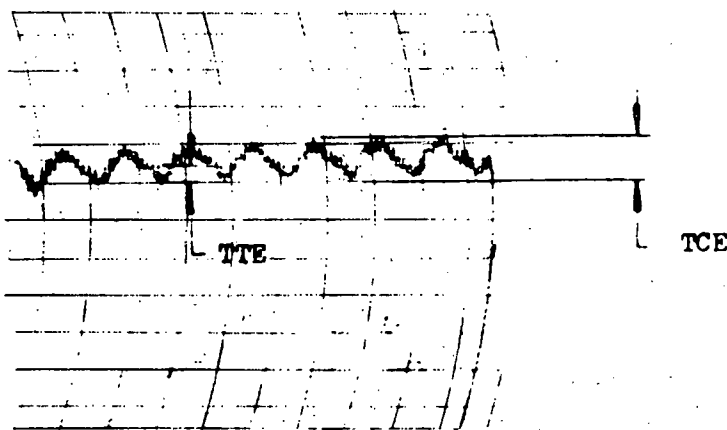


Figure 3. Composite Reading on Fellows No. 4 Redliner Gear Checker

Involute Check

The tooth profiles were checked on a Fellows 12-M Involute Machine. They were checked in 3-degree increments at 5000 to 1 magnification. The involute profile measuring instrument duplicates the generation of an involute curve from the base circle. The probe contacts the tooth profile and measures a deviation from true involute on a roll tape. Profile variations are measured in the traverse plane.

The check was made by holding the pinion in a small drill chuck on one journal. The drill chuck was fitted to a tapered adaptor that would replace the bottom center in the 12-M Machine. The drill chuck was lined up in the adaptor first by setting the tapered adaptor in a precision V-block with a ball bearing in the end against a plate. A 0.0350-inch pin was set in the chuck and was lined up with a high magnification indicator to run 0.00008 inch TIR. Then with the drill chuck lined up in the adaptor, a pinion was inserted in chuck and the other journal was indicated to run a TIR of 0.00040-inch or better.

After the pinion had been aligned in the chuck, the adaptor was set in the bottom center position in the machine. The machine was set by blocks figured from the base circle. The involute profile was rolled from 0 degree or radial (Figure 4). A standard stylus was thinned by hand for the pointer. On the first pinion rolled, the base circle was changed by only 0.0001 inch to keep the involute itself within 0.0001. This accuracy indicated that the pressure angle on the grinding wheel was good. The charts from radial showed approximately 48 to 50 degrees of roll.

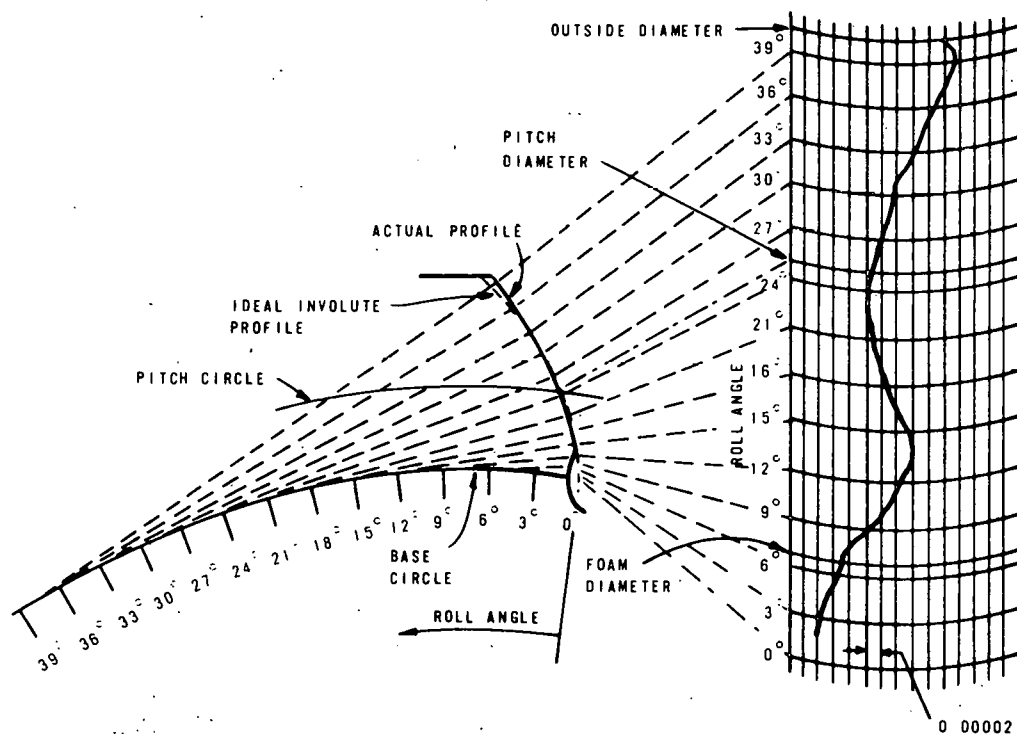


Figure 4. Profile Recording on Fellows 12-M Involute Machine

Surface Finish

Because of the part's minute size, it was impossible to obtain a quantitative inspection of the tooth surface finish. Three approaches were taken to qualify the surface finish produced.

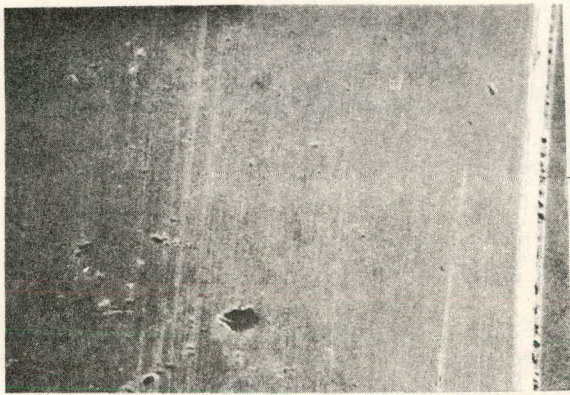
- A random sample of parts was checked on an involute checking machine at Fellows' plant using 5000 to 1 amplification. Charts were made on five of the best 50 pinions ground. These charts were made for the purpose of estimating surface finish only. The part print called for 16AA surface finish on the working surface of the tooth. Since the stylus traced the involute form perpendicular to the lay lines in the tooth and because of the high magnification used, surface roughness can be seen in the chart recording.
- A random sample of five good parts was visually compared to a known standard by Bendix inspection personnel for an interpretation of surface finish.
- Three ground and three hobbled gears were photographed on a scanning electron microscope to compare the surface finish at high magnification. Typical results are shown in Figure 5.

All of the techniques used indicated that better than a 16AA surface finish was obtained.

Deburring

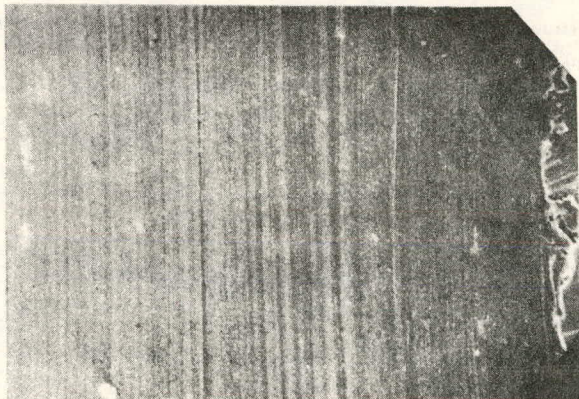
Figure 6 shows a comparison of the burrs generated by hobbing and grinding. The burrs produced at the end, where the cutter exits, and at the crest of the tooth are the most difficult to remove. The burrs in these areas on the hobbled gears are larger, better attached to the parent metal, and much more difficult to remove than the burrs on the ground part.

A sample of ten ground gears were vibratory deburred for one hour in N8 media (fused Al_2O_3) and PC-12B burnishing compound. All of the grinding burrs were removed from the parts with no apparent damage to the surface finish when examined under 25X magnification.

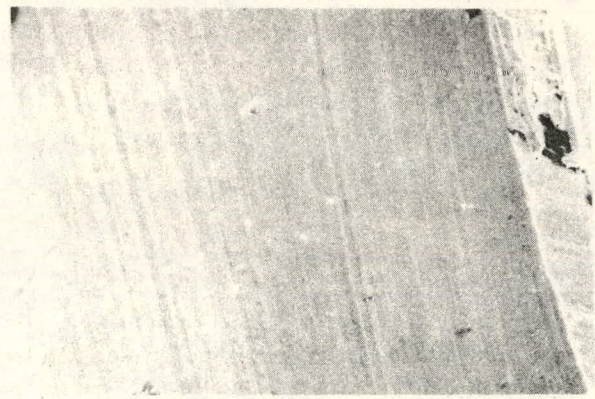


← Crest of tooth

Ground Gear

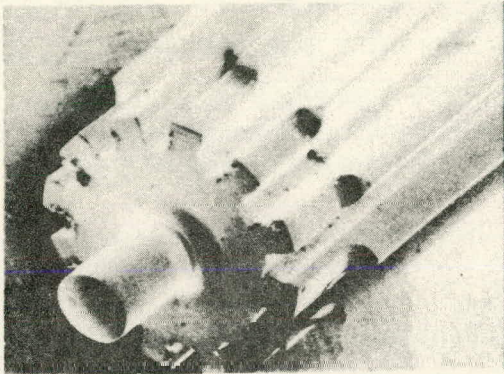


Hobbed Gear, New Hob

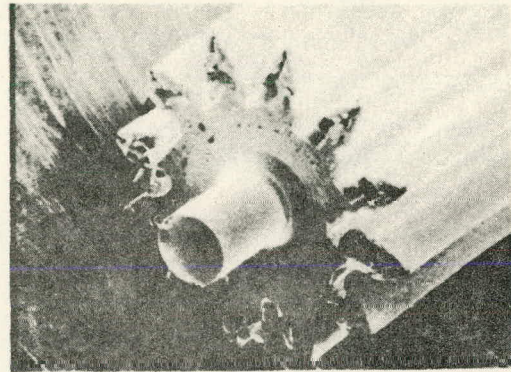


Hobbed Gear, Used Hob

Figure 5. Photographs of Tooth Profile at 200X

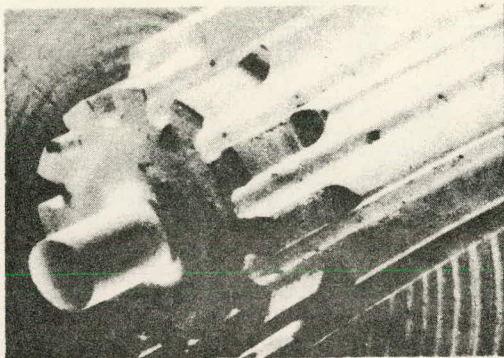


CUTTER ENTRANCE BURR

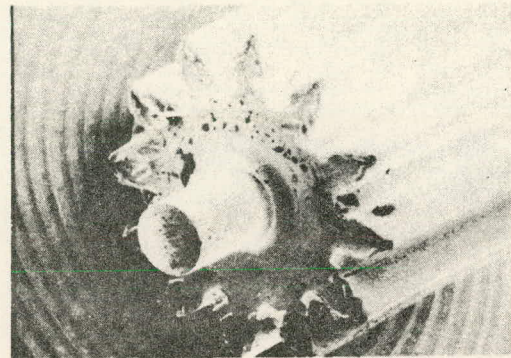


CUTTER EXIT BURR

GEAR CUT WITH NEW HOB - 30X

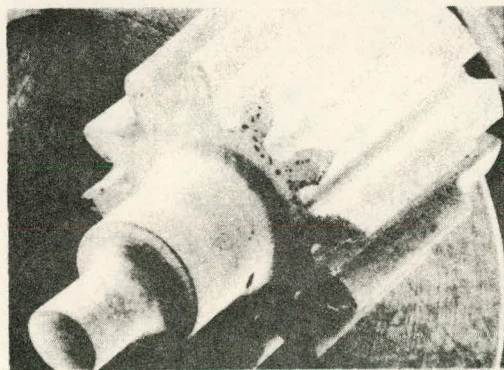


CUTTER ENTRANCE BURR

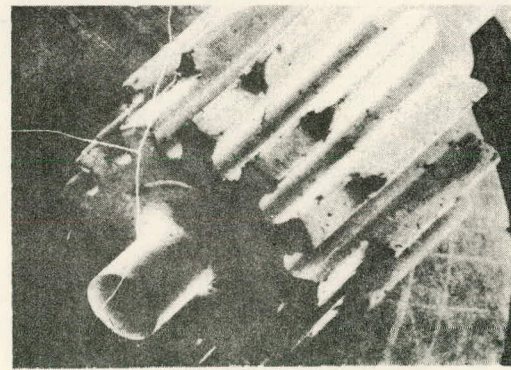


CUTTER EXIT BURR

GEAR CUT WITH USED HOB - 30X



CUTTER ENTRANCE BURR



CUTTER EXIT BURR

GROUND TOOTH SPECIMEN #78 - 30X

Figure 6. Comparison of Burrs Produced by Grinding and Hobbing (17-4ph Stainless Steel, H900 Condition)

Appendix A

DRAWING AY 204473 GRAPHIC GEAR, PINION

PINION GEAR BLANK

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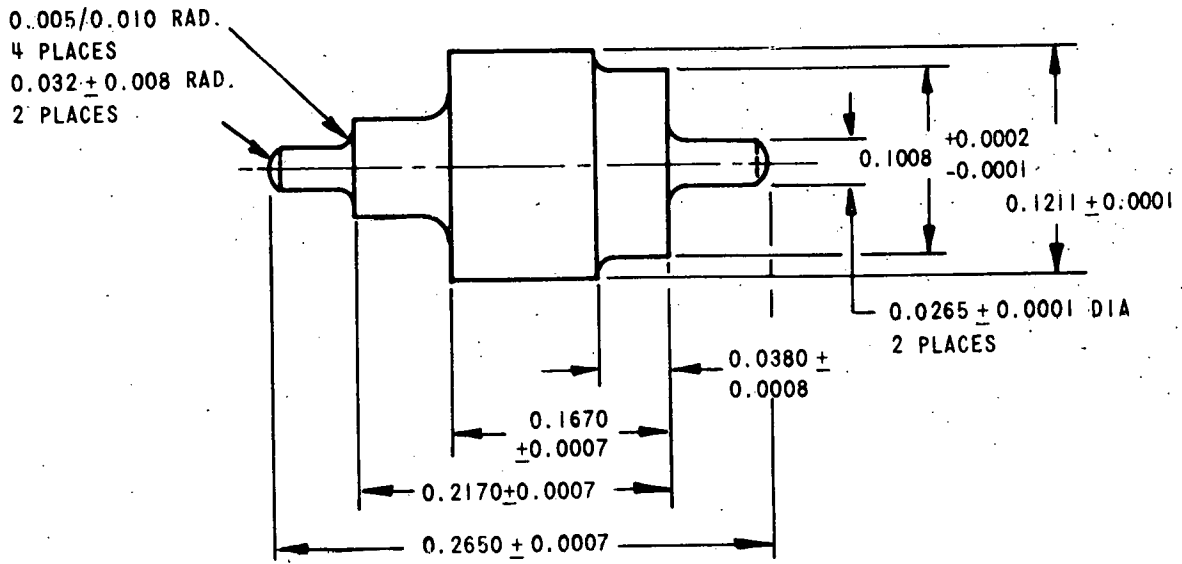


Figure A-1. Pinion Gear Blank

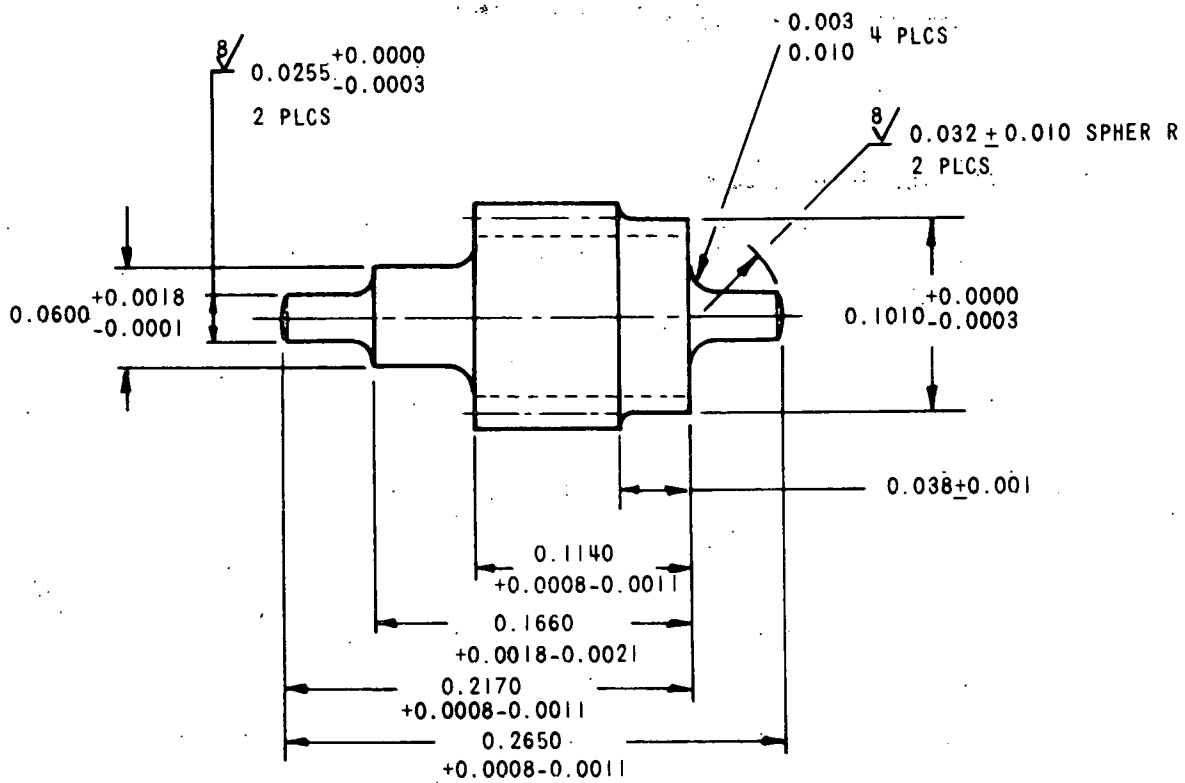
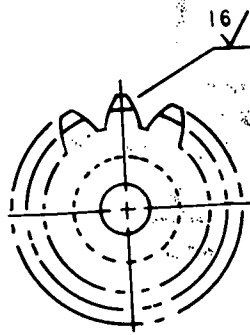


Figure A-2. Graphic Gear, Pinion

Appendix B

COMPOSITE CHARTS FROM FELLOWS NO. 4
REDLINER GEAR CHECKING MACHINE

INVOLUTE PROFILE CHARTS FROM FELLOWS 12-M
INVOLUTE MACHINE

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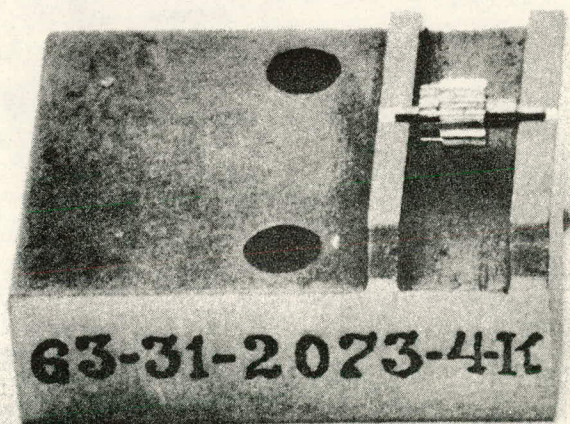
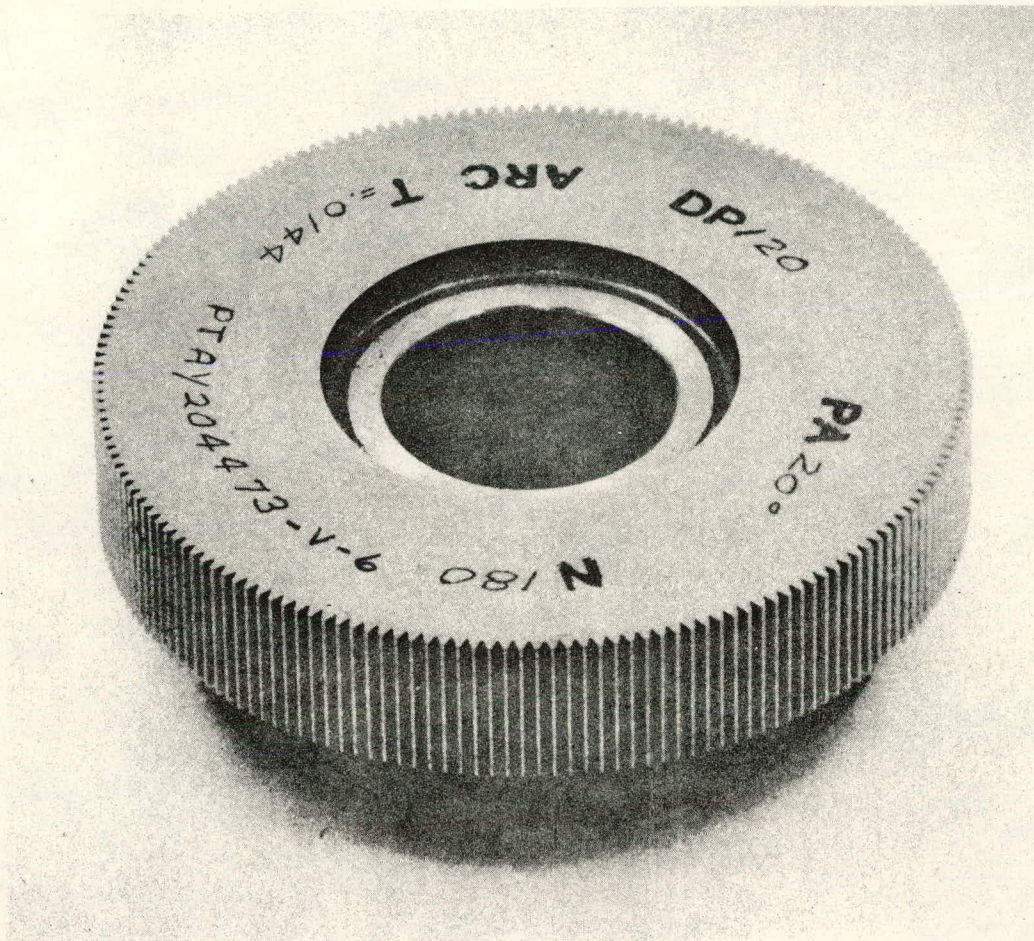


Figure B-1. Master Gear and Staging Fixture for Redliner Gear Checker

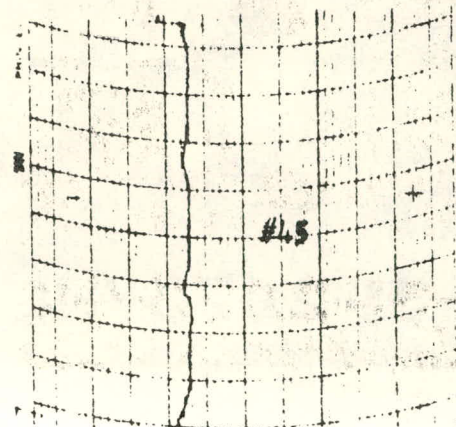
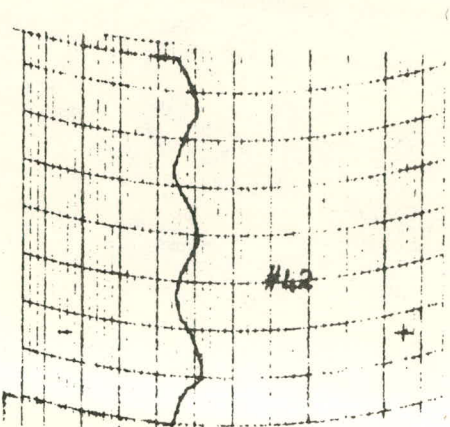
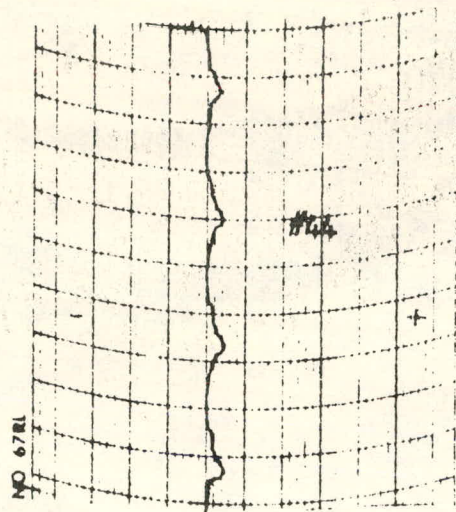
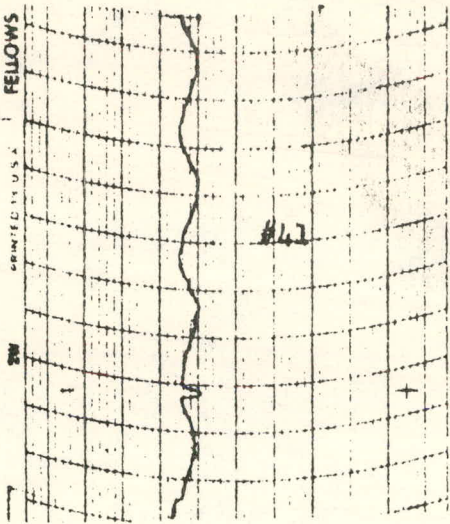
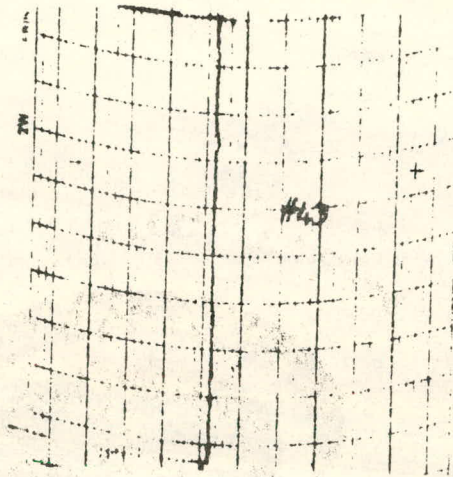
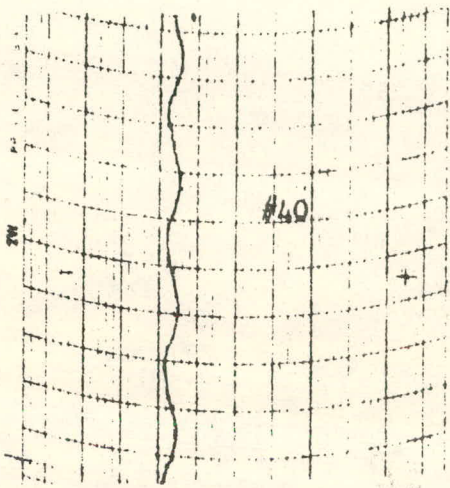


Figure B-2. Composite Readings Obtained at BKC on Fellows No. 4 Redliner Gear Checker

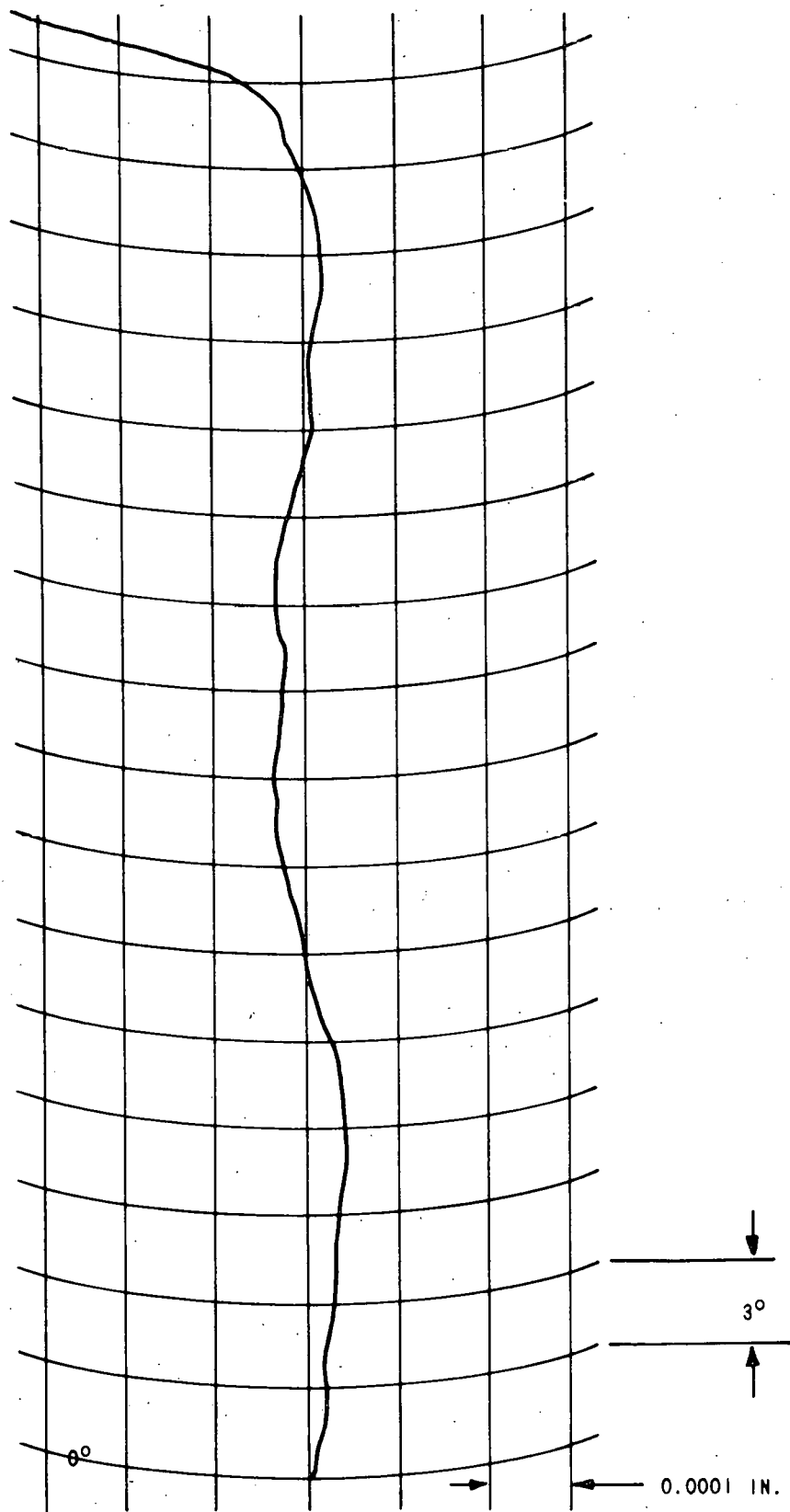


Figure B-3. Typical Involute Profile Recorded on Fellows 12-M Involute Machine

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Appendix C

WHEEL TRUING MECHANISM

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Appendix C

WHEEL TRUING MECHANISM

WHEEL TRUING

A rack form is threaded into the grinding wheel prior to the grinding operation. Since the Fellows No. 4 grinding machine has a separate self-contained truing mechanism, the wheel has to be removed from the grinding machine and mounted on the wheel truing spindle. The diamond dressing tool shown in Figure C-1 has the full form of the rack on it.

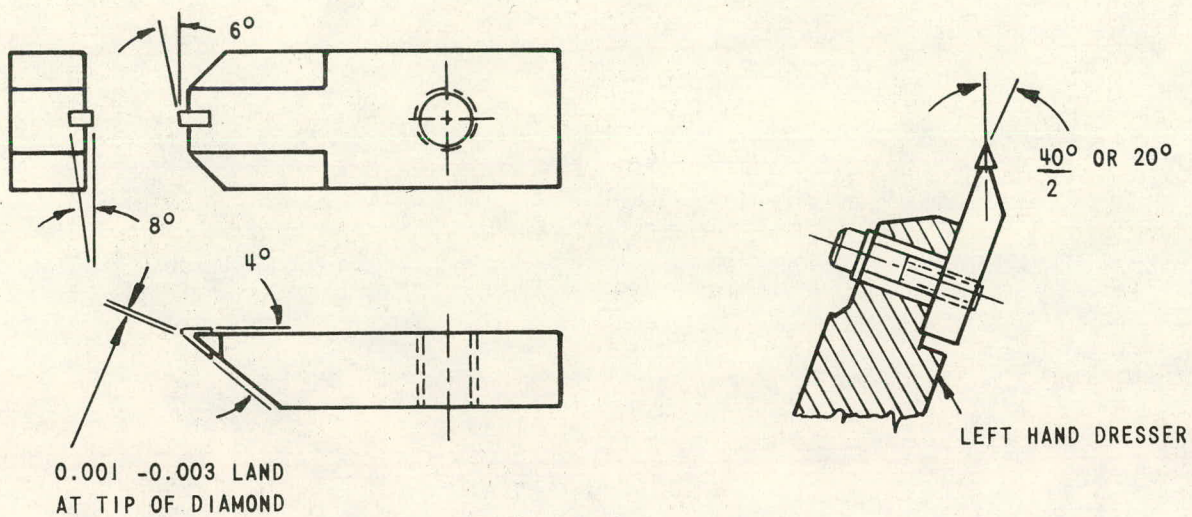


Figure C-1. Full Form Diamond Dressing Tool

The diamond tool is placed in the left-hand holder as shown in Figure C-2. The angle α (which sets the angle of the diamond in the proper attitude to the grinding wheel) is established by setting a spacing block between the dresser and the stop shown. The 0.9481 inch value for M is derived by using the formula

$$M = 3.937 \sin (40^\circ - \text{pressure angle}) - 0.3937.$$

The following set of change gears establishes the proper lead angle on the wheel. The lead angle is equal to the circular pitch of the gear to be ground (or $\frac{\pi}{120} = 0.0261$ inch per revolution of the wheel).

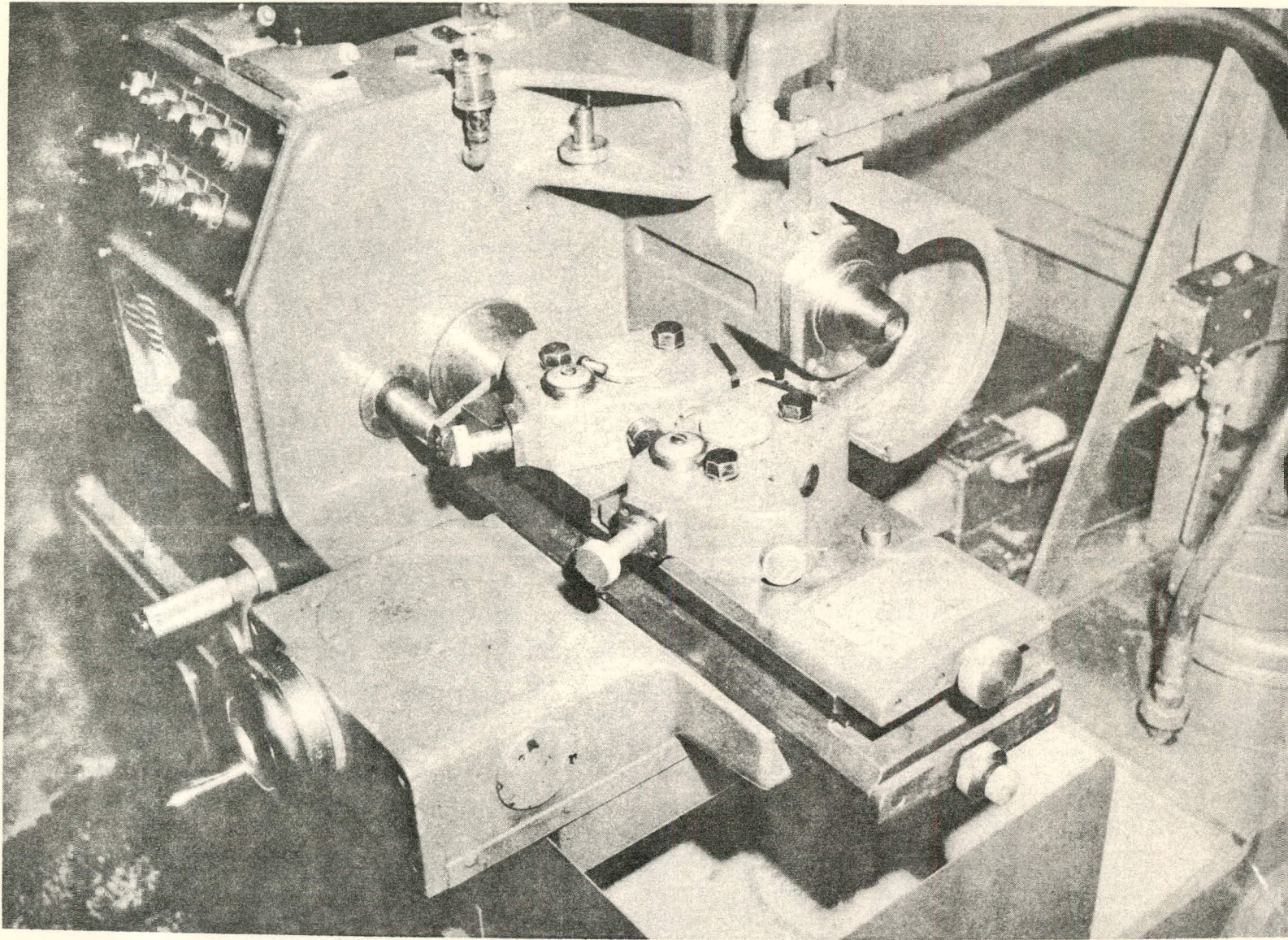
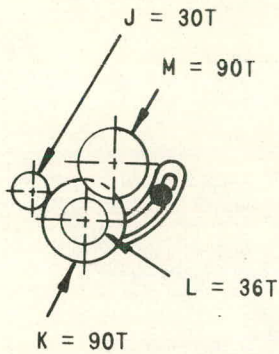


Figure C-2. Wheel Truing Attachment



The travel of the truing slide is set to overtravel the grinding wheel by about 1/4 inch on each end.

The whole depth of the tooth form plus clearance is calculated by the following formula

$$\frac{3.558}{DP} - 1.374 \times \text{flat on diamond}$$

The truing mechanism is turned on, which starts the grinding wheel rotation at the proper speed and the traverse of the truing slide. While the truing slide is traveling from right to left on its dressing stroke, the hand wheel is fed in until it touches the grinding wheel. This is the starting point for the threads on the grinding wheel and the dial setting on the micrometer drum is noted. The hand wheel is fed in 0.0005-inch during the return stroke of the truing slide until the 0.0255-inch full depth is obtained.

The grinding wheel is then removed from the truing mechanism and placed on the wheel head spindle of the machine.

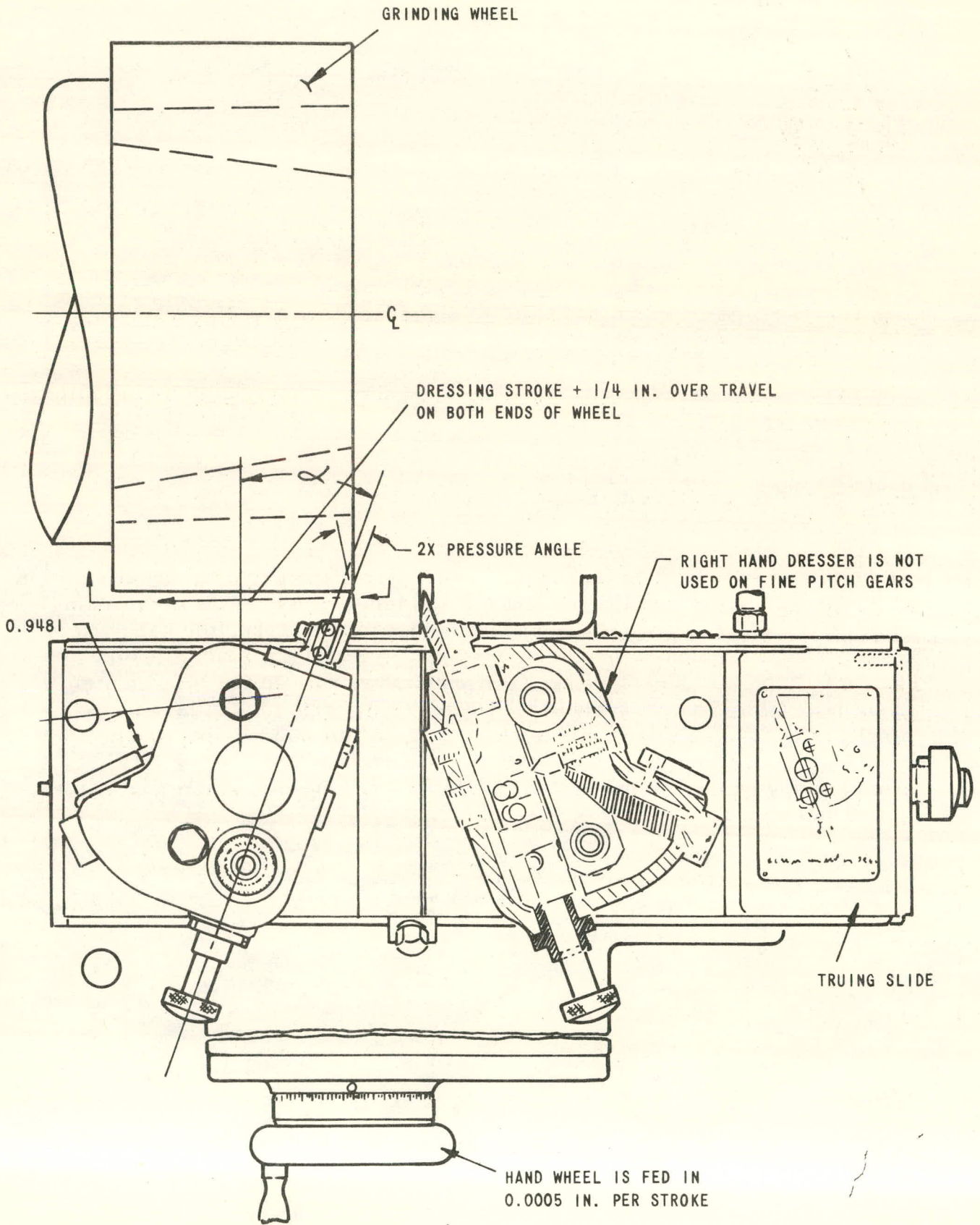


Figure C-3. Wheel Truing Device

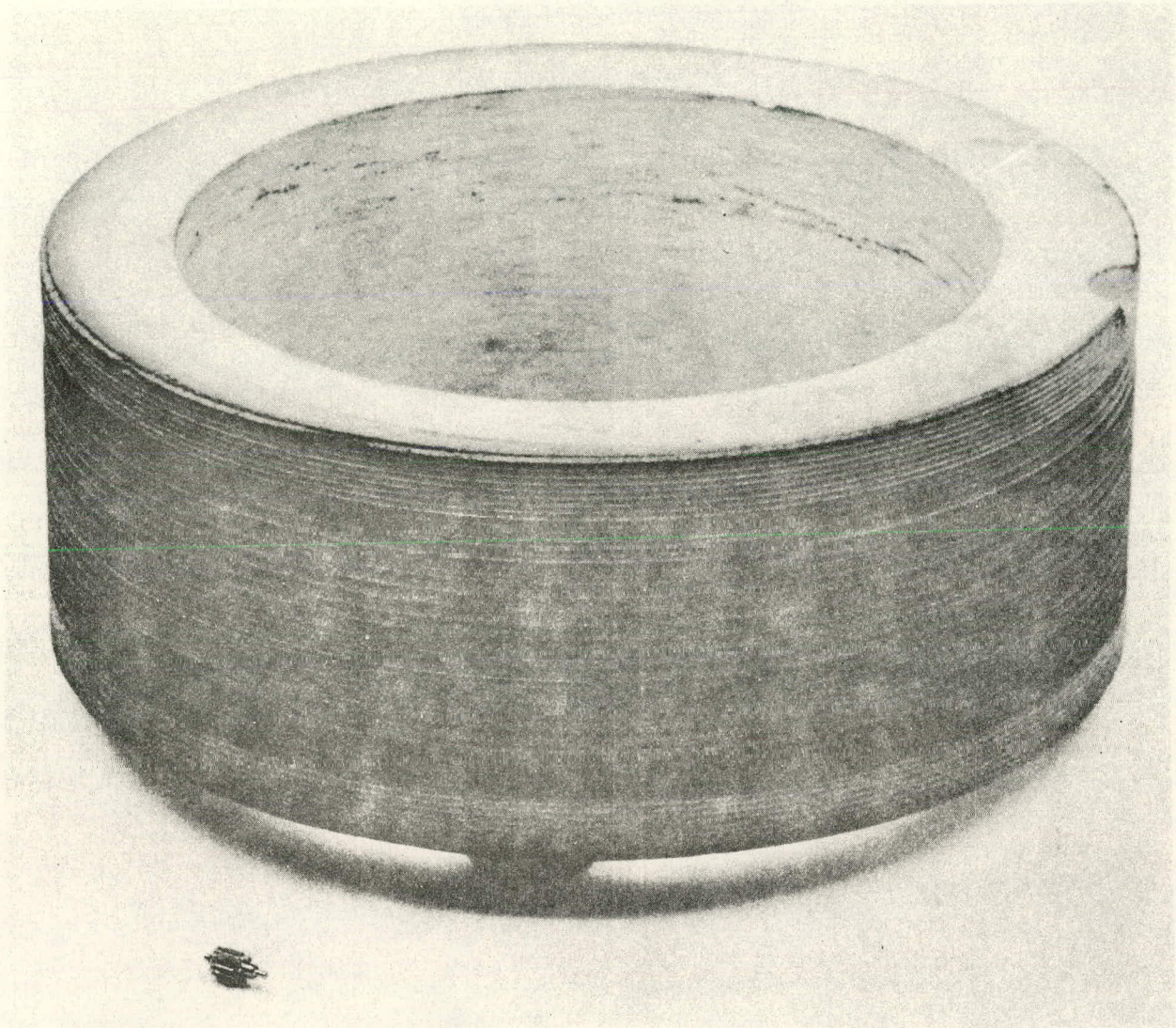


Figure C-4. Photograph of Diamond Dresser and Grinding Wheel

BDX-613-1007

GRINDING MINIATURE
PINION GEARS

Technological Spinoff Report

R. W. Stiles, Project Leader

Project Team:
L. K. Gillespie
D. R. Wachter

Published October 1973

Prepared for the
United States Atomic Energy Commission
Under Contract Number AT(29-1)-613 USAEC



**Kansas City
Division**

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PINION GEARS

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Department 822

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Technological Spinoff Report

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GRINDING MINIATURE PINION GEARS

BDX-613-1007, UNCLASSIFIED Technological Spinoff Report, Published
October 1973

Prepared by R. W. Stiles, D/822

Although grinding inherently produces a better involute form and finer surface finish than other basic gear fabrication methods, equipment and experience in grinding 120-pitch gears with 0.100 inch pitch diameter were not available when Bendix Kansas City placed a process development contract with the Fellows Company. Bendix had been producing a functional miniature gear by hobbing, but the required surface finish was borderline and burrs on the part were difficult to remove. As a result of this project, a repeatable process was developed for grinding the tooth form and maintaining a 16AA surface finish with minimum burrs. An experimental machine was used in this process development; production equipment is not yet available in U. S. industry for this process but could be developed.

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THE BENDIX CORPORATION

KANSAS CITY DIVISION

KANSAS CITY, MISSOURI

A prime contractor for the
Atomic Energy Commission

Contract Number AT(29-1)-613 USAEC

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CONTENTS

Section	Page
SUMMARY	11
DISCUSSION	13
SCOPE AND PURPOSE	13
PRIOR WORK	13
ACTIVITY	14
<u>Setup and Grinding</u>	16
ACCOMPLISHMENTS	16
<u>Cycle Time</u>	16
<u>Inspection Data</u>	19
<u>Deburring</u>	21
APPENDICES	
A. DRAWING AY204473 GRAPHIC GEAR, PINION	25
B. COMPOSITE CHARTS; INVOLUTE PROFILE CHARTS.	29
C. WHEEL TURNING MECHANISM	35

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ILLUSTRATIONS

Figure		Page
1	Bendix PN 204473-101 (P-64633)	14
2	Generation of Involute Profiles	15
3	Composite Reading on Fellows Number 4 Redliner Gear Checker.	19
4	Profile Recording on Fellows 12-M Involute Machine	20
5	Photographs of Tooth Profile at 200X (P-74711)	22
6	Comparison of Burrs Produced by Grinding and Hobbing (P-74710)	23
A-1	Pinion Gear Blank	27
A-2	Graphic Gear, Pinion	28
B-1	Master Gear and Staging Fixture for Redliner Gear Checker (P-64636)	31
B-2	Composite Readings Obtained at BKC on Fellows Number 4 Redliner Gear Checker	32
B-3	Typical Involute Profile Recorded on Fellows 12-M Involute Machine	33
C-1	Full Form Diamond Dressing Tool	37
C-2	Wheel Truing Attachment (P-64631).	38
C-3	Wheel Truing Device	40
C-4	Photograph of Diamond Dresser and Grinding Wheel (P-64635).	41

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TABLE

Number		Page
1	Inspection Data for Parts Ground in Support of Development Contract.	17

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SUMMARY

Part Number 204473-101 (a 120-pitch, 12-tooth pinion gear) is one of a family of similar gears used in small escapement assemblies. The timing repeatability of the escapement assemblies is influenced by the accuracy and surface finish on the gearing. Consequently, this pinion and the other gears in the escapement assemblies require a 16 microinch (AA) surface finish on the working surfaces of the teeth and a tooth form to AGMA quality class 11b+. The blank for the 120 pitch gear is extremely small (0.100 PD) and made from 17-4 PH stainless steel, heat treated to a hardness of Rockwell "C" 41 minimum.

Bendix is producing this gear by hobbing using a Class AAA hob. Although a functional gear is being produced when the hobs are sharp, the required surface finish is borderline and deburring is a significant portion of the fabrication time. The most logical step for improvement of the process then was grinding the tooth form. A process development contract was placed with the Fellows Company (formerly the Fellows Gear Shaper Company) to develop a repeatable process for grinding the tooth form and maintaining a 16 microinch (AA) surface finish with minimum burrs. Fellows was to develop any tooling necessary for an experimental grinder in their shop and produce 50 pinions to print tolerances.

Grinding inherently produces a better involute form, a better tooth-to-tooth error (TTE), a better total composite error (TCE), and finer surface finishes than other basic gear fabrication methods.

Generation grinding using a threaded grinding wheel is especially adaptable to high volume production work. This process operates on the same principle as hobbing, in that the threaded grinding wheel acts like a rack with the lead angle in the thread form allowing continuous action without indexing.

Grinding 120 pitch gears presented no basic problem to the Fellows Company since the experimental machine used in this development project was built to grind fine pitch master gears and shaper cutters. This was the first attempt by anyone, however, to grind a gear with a 0.100 inch pitch diameter.

The endeavor was successful. This was the first time the tooth form on a gear this size had been produced by grinding. One hundred fifty blanks were sent to Fellows to produce the required fifty. Ninety-one gears were ground during this project; 61 were dimensionally acceptable and 30 were not. Out of the 30 unacceptable parts, 15 were lost during setup.

The actual machining time required to grind the tooth form was 5.6 minutes, as compared to 2.4 minutes for hobbing. Production calculations indicated, however, that the grinding time could be reduced 40 percent below that used in the development of this process by increasing the feed rates.

Of the 50 good parts required by contract, 74 percent fell within a range of 0.0002 to 0.0004 inch on the TCE, with only 12 percent exceeding 0.0004 inch. Seventy-six percent of the 50 parts were within a spread of +0.0002 -0.0003 inch from nominal on the over pin measurement of the pitch diameter.

Three approaches were taken to qualify the surface finish produced: five good parts were checked on an involute checking machine at Fellows' plant using 5000 to 1 amplification; five good parts were visually compared to a known standard by Bendix inspection personnel for a visual interpretation of surface finish; and three ground and three hobbled gears were photographed on a scanning electron microscope to compare the surface finish at high magnification.

All of the techniques used indicated that better than a 16AA surface finish was obtained.

A sample of ten ground gears was vibratory deburred for one hour in N8 media (fused Al_2O_3) and PC-12B burnishing compound. All of the grinding burrs were removed from the parts with no apparent damage to the surface finish when examined under 25X magnification.

Although a process was developed by the Bendix Kansas City Division and the Fellows Company to grind miniature pinion gears, production equipment with this capability is not available. Prior to this project Bendix made a through search of the machine tool industries in both the United States and Europe for a gear grinder capable of producing this pinion gear. The response was negative and no interest could be generated because of the limited marketing potential for such a machine. The grinder Fellows used in this project was an experimental machine built for their internal use. The lack of refinement in this machine limited its application to production use.

All tests performed on the escapement units have shown that functional gears are being produced by hobbing. For this reason, and because production grinding equipment for this size and type of gear is not presently available, changing the fabrication process is not warranted at this time. However, the development of the grinding process has made the parameters available for use in the design and fabrication of a production machine if the future need arises.

DISCUSSION

SCOPE AND PURPOSE

Part Number (PN) 204473-101 (a 120-pitch, 12-tooth pinion gear) is one of a family of similar gears used in escapement assemblies. The timing repeatability of the escapement assemblies is influenced by the accuracy and surface finish on the gearing. Consequently this pinion and the other gears in the escapement assemblies require a 16 microinch (AA) surface finish on the working surfaces of the teeth and a precision tooth form to AGMA quality class 11b+. Small commercial pinions of this pitch and size are fabricated by hobbing and are generally made of soft material such as brass or mild steel. For this reason little effort had been made by industry to develop grinding equipment for this size gear. The blank for the 120 DP gear is extremely small (0.100 PD) and made from 17-4 PH stainless steel heat treated to a hardness of Rockwell "C" 41 minimum which places it at the upper limits of machinability. Figure 1 shows the relative size of PN 204473-101.

Bendix was producing this gear by hobbing, using a Class AAA hob. Although a functional gear was being produced when the hobs were sharp, the required surface finish was borderline and deburring had become a major problem. Therefore the most logical step for improvement of the process was to grind the tooth form. A process development contract was placed with the Fellows Company (formerly the Fellows Gear Shaper Company) to develop a repeatable process for grinding the tooth form and maintaining a 16 microinch (AA) surface finish with minimum burrs. Fellows was to develop any tooling necessary for an experimental grinder in their shop and produce 50 pinions to print tolerances.

PRIOR WORK

Gear grinding is one of the earliest methods used to finish gears.¹ Grinding inherently produces a better involute form, a better tooth-to-tooth error (TTE), a better total composite error (TCE), and finer surface finishes than other basic gear fabrication methods. Gear grinding is used when the need for any of all of the above conditions exist. As the material in a blank becomes harder, grinding may be the only method available to produce the gear teeth form. Although grinding can be performed at any

¹Tool Engineers Handbook, 2nd Edition, American Society of Tool and Manufacturing Engineers, McGraw-Hill, 1959, pp. 44-87.

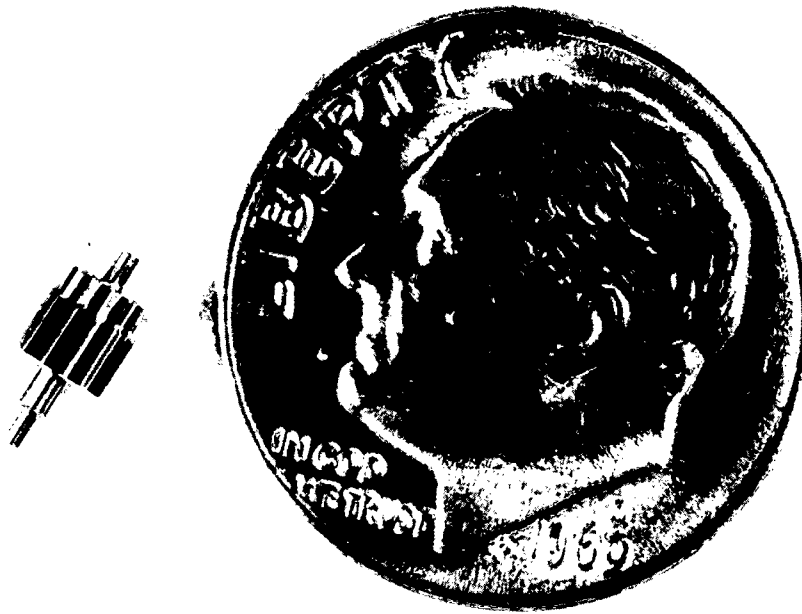


Figure 1. Bendix PN 204473-101

hardness range, optimum grindability is from RC 40 to RC 55.² Coarse pitch gears (up to 48 DP) require prefinishing operations, such as hobbing or shaping preparatory to grinding, but fine pitch gears (48 DP and finer) are ground from solid blanks.

Generation grinding (Figure 2), using a threaded grinding wheel, is especially adaptable to high-volume production work. This process operates on the same principle as hobbing in that the threaded grinding wheel acts like a rack with the lead in the thread form allowing continuous grinding action without indexing.

ACTIVITY

Grinding 120-pitch gears presented no problem to the Fellows Company since they grind master gears and shaper cutters of this pitch for their

²Michalec, George W., Precision Gearing, Theory and Practice, John Wiley & Sons, 1966, p. 481.

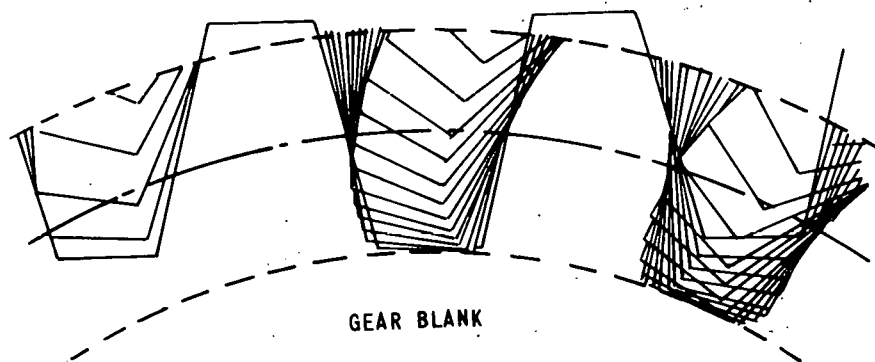


Figure 2. Generation of Involute Profiles

customers. This was the first attempt by anyone, however, to grind a gear with a 0.100-inch pitch diameter. The part presented unique problems with respect to grinding because of its minute size. The blank had to be located and driven off two 0.0261-inch-diameter journals. The proportion of the grinding wheel diameter to the part diameter created problems in the design and fabrication of the workholding centers. To grind to full depth with the wheel, the outside diameter on the workholding centers had to be thinned to 0.075-inch diameter for 1/4-inch length; there was also an apparent danger that both the centers and the work piece might spring away from the grinding wheel due to grinding pressure. Further complicating this operation was the difficulty of applying sufficient holding pressure from the machine's tailstock to drive the gear during the machining cycle.

The machine used in this project was an experimental fine pitch gear grinder. The grinding wheel selected (Norton 38A400-J9VG) was 400-grit aluminum oxide. The diameter of the wheel is 4 inches. A rack form (2 times the pressure angle, or 40°) was threaded into the wheel at a precalculated lead angle (see Appendix C for description of wheel truing and dressing operation). The workholding device was mounted in two female centers; the device consists of a driving center mounted in the headstock and a driven center mounted in the tailstock. The gear blank was placed in the female centers and pressure was applied from the tailstock to keep the blank from rotating during grinding. The work holding centers were horizontally mounted on the machine and the grinding wheel spindle was mounted vertically. While the work spindle rotates the grinding wheel spindle rotates, strokes axially across the part, and feeds in at a controlled amount at the end of each stroke. This action continues until full depth of the gear tooth is reached at which time the wheel head automatically retracts. The lead angle on the grinding wheel allows continuous action without indexing. Only a small portion of the grinding wheel is used at a time. As the wheel dulls the wheel head is shifted vertically (tangential about 0.050 inch) to a new area.

The surface speed was 3769 feet per minute. The workpiece rotated at 300 rpm and the grinding wheel at 3600 rpm. The wheel head slide speed was 0.0029 inch per revolution of the workpiece and the infeed rate was 0.0008 per stroke.

Setup and Grinding

The actual grinding of the pinions from setup to completion took place in a 3-week period. In first setting up the job the originally calculated wheel-head speed of 2 seconds per 0.175 inch stroke was too fast and the wheelhead was feeding in the middle of the stroke. The speed was changed to 9 seconds per stroke which corrected the problem. Drag in the tailstock live center and insufficient drive pressure was hindering the rotation of the pinion gear during the machining cycle. The tailstock center had to be lapped four times before it ran free enough to allow the pinion to rotate with the driving headstock center.

About twenty-five pinions were required to debug the process and tooling. Once the initial setup problems had been corrected, however, little trouble was encountered in grinding the tooth form.

ACCOMPLISHMENTS

A total of 91 gears were ground during the course of this project; 61 were within print tolerance and 30 were scrapped. Of the 30 scrapped parts, 15 were lost during setup. Seventy-four percent of the 50 good parts required by the contract fell within a range of 0.00020 to 0.00040 inch on the TCE with only 12 percent exceeding 0.0004 inch. Seventy-six percent of the 50 parts fell within a range of +0.00020 to -0.00030 inch from the nominal on the over pin measurement of the pitch diameter. See Table 1.

Cycle Time

When the machining time of the grinding operation was compared to hobbing, only the actual machine cycle time was compared since all other functions would have been similar for both methods. The cycle time for hobbing after engaging the machine is 2.4 minutes and the average cycle time established during the course of this project for grinding was 5.6 minutes at the feed rates used. The grinding feed rates used were conservative; by increasing the wheelhead slide speed and the infeed rate, the cycle time could be reduced by as much as 40 percent. To verify this, the last three gears were ground at an infeed rate of 0.0012 inch per stroke. The greater infeed rate had no effect on surface finish, TCE, or pitch diameter.

Table 1. Inspection Data for Parts Ground in Support of Development Contract

Part* Number	TCE** Limit 0.00055 Inch	DOP*** 0.1233 to 0.1219 Inch	Good
1	Did not rotate		
2	Did not rotate		
3	Did not rotate		
4	0.00040	0.12240	X
5	0.00060	0.12190	
6	0.00040	0.12160	
7	0.00040	0.12170	
8	Did not rotate	Did not rotate	
9	0.00035	0.12320	X
10	0.00040	0.12320	X
11	Machine malfunction	Machine malfunction	
12	Ground flat	Ground flat	
13	0.00056	0.12080	
14	0.00015	0.12580	
15	Not checked	0.12400	
16	0.00065	0.12290	
17	Not checked	0.12800	
18	Machine malfunction	Machine malfunction	
19	0.00060	Not checked	
20	0.00035	0.12230	X
21	0.00055	0.12190	X
22	Machine malfunction	Machine malfunction	
23	0.00030	0.12150	
24	0.00055	0.12180	
25	0.00080	0.12280	
26	0.00018	0.12200	X
27	0.00018	0.12260	X
28	0.00045	0.12174	
29	0.00015	0.12250	X
30	0.00050	0.12160	
31	0.00040	0.12280	X
32	0.00020	0.12280	X
33	0.00025	0.12260	X
34	0.00030	0.12260	X
35	0.00040	0.12265	X
36	0.00040	0.12260	X
37	0.00025	0.12250	X
38	0.00028	0.12240	X
39	0.00030	0.12260	X
40	0.00025	0.12250	X
41	0.00040	0.12240	X
42	0.00040	0.12240	X
43	0.00020	0.12260	X
44	0.00015	0.12260	X
45	0.00018	0.12240	X
46	0.00030	0.12250	X

Table 1. Continued. Inspection Data for Parts Ground in Support of Development Contract

Part Number	TCE** Limit 0.00055 Inch	DOP*** 0.1233 to 0.1219 Inch	Good
47	0.00035	0.12190	X
48	0.00045	0.12190	X
49	0.00020	0.12214	X
50	0.00025	0.12234	X
51	0.00030	0.12255	X
52	0.00030	0.12255	X
53	0.00030	0.12260	X
54	0.00025	0.12260	X
55	0.00045	0.12260	X
56	0.00030	0.12267	X
57	0.00020	0.12267	X
58	0.00030	0.12260	X
59	0.00040	0.12260	X
60	0.00025	0.12260	X
61	0.00035	0.12260	X
62	0.00015	0.12260	X
63	No teeth	No teeth	
64	Machine malfunction	Machine malfunction	
65	Machine malfunction	Machine malfunction	
66	0.00025	0.12230	X
67	0.00020	0.12220	X
68	0.00020	0.12200	X
69	Machine malfunction	Machine malfunction	
70	0.00015	0.12240	X
71	0.00050	0.12240	X
72	0.00025	0.12240	X
73	0.00020	0.12300	X
74	0.00040	0.12260	X
75	0.00035	0.12260	X
76	Machine malfunction	Machine malfunction	
77	0.00045	0.12160	
78	0.00035	0.12260	X
79	0.00035	0.12330	X
80	0.00050	0.12342	
81	0.00025	0.12330	X
82	0.00035	0.12260	X
83	0.00035	0.12300	X
84	0.00025	0.12330	X
85	0.00035	0.12260	X
86	0.00040	0.12260	X
87	0.00020	0.12290	X
88	0.00050	0.12290	X
89****	0.00035	0.12160	
90****	0.00030	0.12260	X
91****	0.00040	0.12285	X

*Parts are listed in the order that they were ground.
 **The composite check was made on a No. 4 Fellows Redliner Gear Checker at 800 to 1 amplification.
 ***The over pin measurements were made using 0.015-inch-diameter pins and a super-micrometer.
 ****Ground at an infeed rate of 0.0012 inch per stroke.

Inspection Data

Pitch Diameter and Composite Check

The two basic checks required on the pinion gears consisted of a composite check and a pitch diameter check. The total composite error (TCE) and tooth-to-tooth error (TTE) were checked on a Fellows No. 4 Red Liner at 800 to 1 amplification (Figure 3). The part was held in a special V-block fixture and rolled with a 120 DP, 1.500-inch pitch diameter master gear. The pressure was set at 4 ounces. One of the pinions (Number 7) was selected as a master for both the Red Liner check and pitch diameter check. The No. 7 master pinion and at least two other pinions were checked each day to maintain the sizing on the Red Liner and to ensure that the machine setup was not disturbed during the night shift hours.

The pitch diameter of the pinions was checked over 0.0150-inch-diameter pins on a super-micrometer. The anvil pressure was set at 2 to 2-1/2 ounces. The required pitch diameter limits were 0.1233 to 0.1219 inch. This gave a tooth thickness at the pitch diameter of 0.01399 to 0.01327 inch.

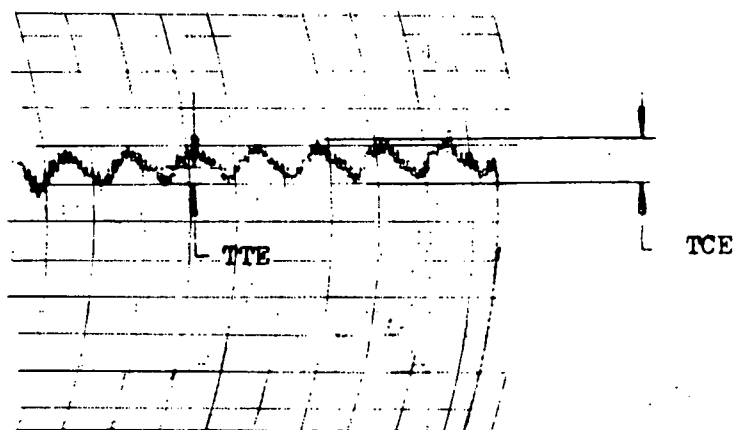


Figure 3. Composite Reading on Fellows No. 4 Redliner Gear Checker

Involute Check

The tooth profiles were checked on a Fellows 12-M Involute Machine. They were checked in 3-degree increments at 5000 to 1 magnification. The involute profile measuring instrument duplicates the generation of an involute curve from the base circle. The probe contacts the tooth profile and measures a deviation from true involute on a roll tape. Profile variations are measured in the traverse plane.

The check was made by holding the pinion in a small drill chuck on one journal. The drill chuck was fitted to a tapered adaptor that would replace the bottom center in the 12-M Machine. The drill chuck was lined up in the adaptor first by setting the tapered adaptor in a precision V-block with a ball bearing in the end against a plate. A 0.0350-inch pin was set in the chuck and was lined up with a high magnification indicator to run 0.00008 inch TIR. Then with the drill chuck lined up in the adaptor, a pinion was inserted in chuck and the other journal was indicated to run a TIR of 0.00040-inch or better.

After the pinion had been aligned in the chuck, the adaptor was set in the bottom center position in the machine. The machine was set by blocks figured from the base circle. The involute profile was rolled from 0 degree or radial (Figure 4). A standard stylus was thinned by hand for the pointer. On the first pinion rolled, the base circle was changed by only 0.0001 inch to keep the involute itself within 0.0001. This accuracy indicated that the pressure angle on the grinding wheel was good. The charts from radial showed approximately 48 to 50 degrees of roll.

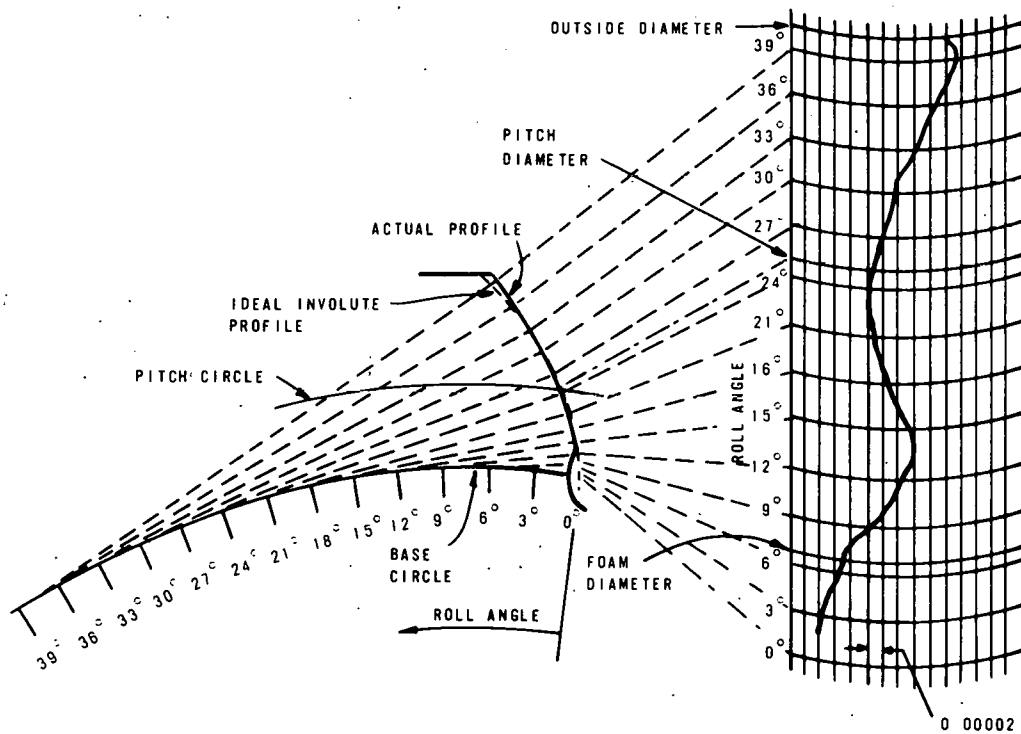
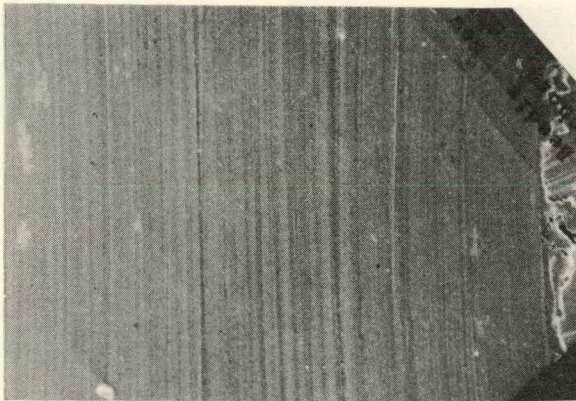


Figure 4. Profile Recording on Fellows 12-M Involute Machine

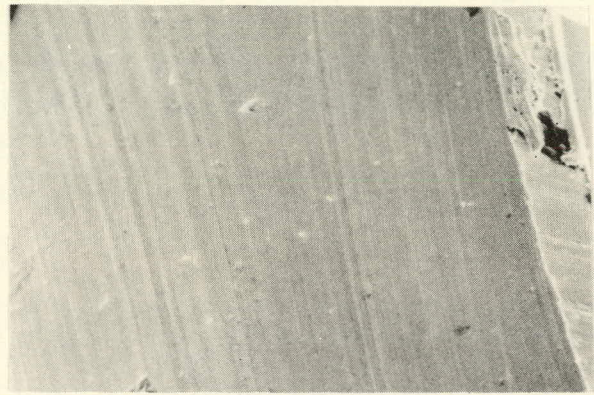


Crest of tooth

Ground Gear



Hobbed Gear, New Hob



Hobbed Gear, Used Hob

Figure 5. Photographs of Tooth Profile at 200X

Surface Finish

Because of the part's minute size, it was impossible to obtain a quantitative inspection of the tooth surface finish. Three approaches were taken to qualify the surface finish produced.

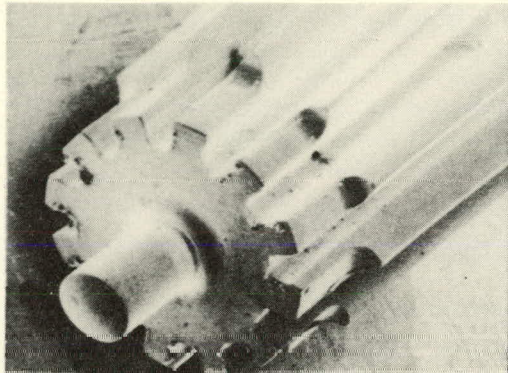
- A random sample of parts was checked on an involute checking machine at Fellows' plant using 5000 to 1 amplification. Charts were made on five of the best 50 pinions ground. These charts were made for the purpose of estimating surface finish only. The part print called for 16AA surface finish on the working surface of the tooth. Since the stylus traced the involute form perpendicular to the lay lines in the tooth and because of the high magnification used, surface roughness can be seen in the chart recording.
- A random sample of five good parts was visually compared to a known standard by Bendix inspection personnel for an interpretation of surface finish.
- Three ground and three hobbled gears were photographed on a scanning electron microscope to compare the surface finish at high magnification. Typical results are shown in Figure 5.

All of the techniques used indicated that better than a 16AA surface finish was obtained.

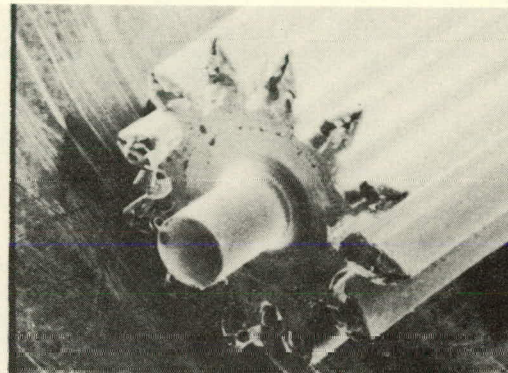
Deburring

Figure 6 shows a comparison of the burrs generated by hobbing and grinding. The burrs produced at the end, where the cutter exits, and at the crest of the tooth are the most difficult to remove. The burrs in these areas on the hobbled gears are larger, better attached to the parent metal, and much more difficult to remove than the burrs on the ground part.

A sample of ten ground gears were vibratory deburred for one hour in N8 media (fused Al_2O_3) and PC-12B burnishing compound. All of the grinding burrs were removed from the parts with no apparent damage to the surface finish when examined under 25X magnification.

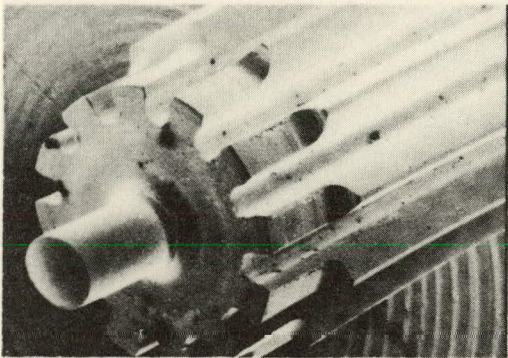


CUTTER ENTRANCE BURR

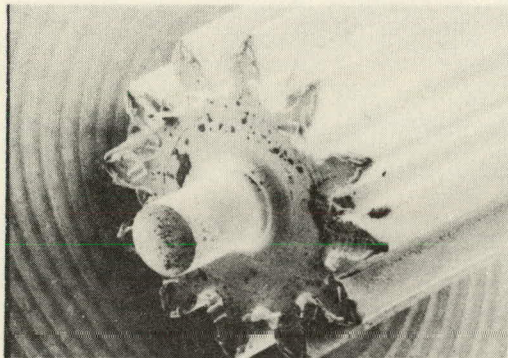


CUTTER EXIT BURR

GEAR CUT WITH NEW HOB - 30X

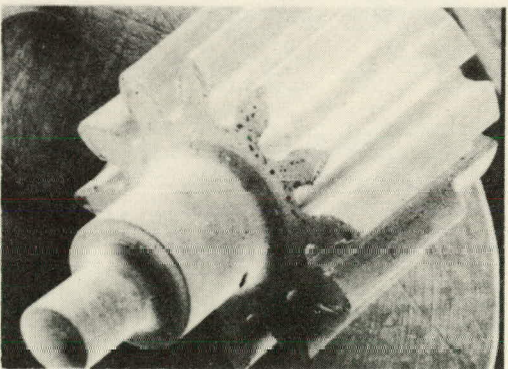


CUTTER ENTRANCE BURR

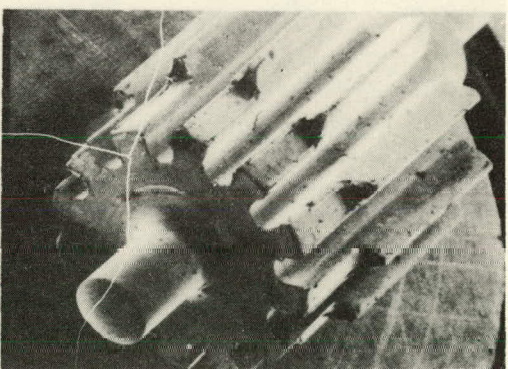


CUTTER EXIT BURR

GEAR CUT WITH USED HOB - 30X



CUTTER ENTRANCE BURR



CUTTER EXIT BURR

GROUND TOOTH SPECIMEN #78 - 30X

Figure 6. Comparison of Burrs Produced by Grinding and Hobbing (17-4ph Stainless Steel, H900 Condition)

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Appendix A

DRAWING AY 204473 GRAPHIC GEAR, PINION

PINION GEAR BLANK

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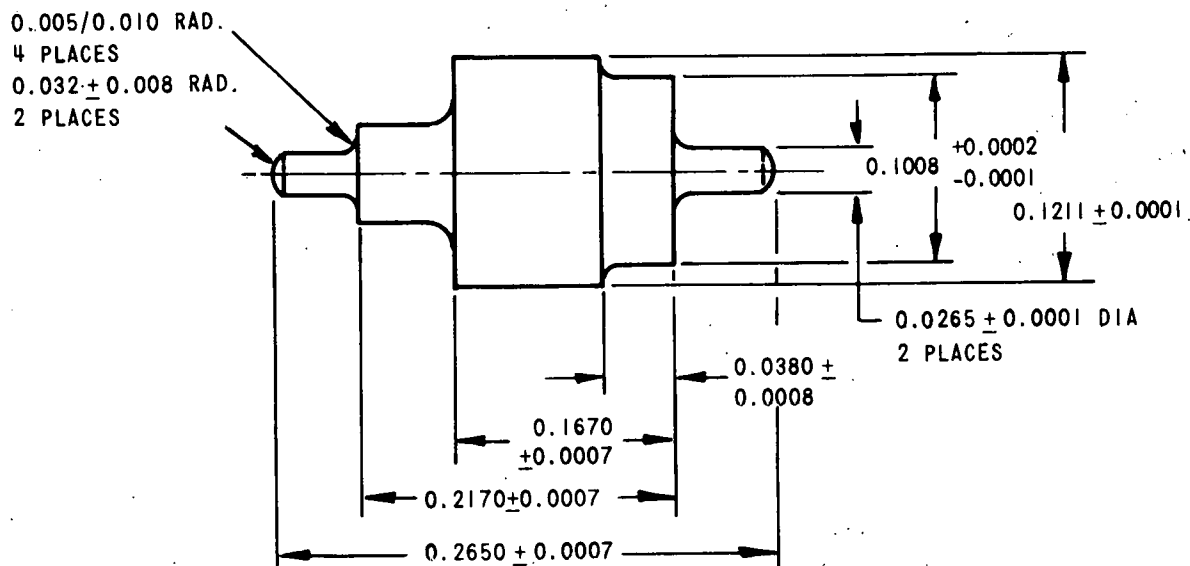


Figure A-1. Pinion Gear Blank

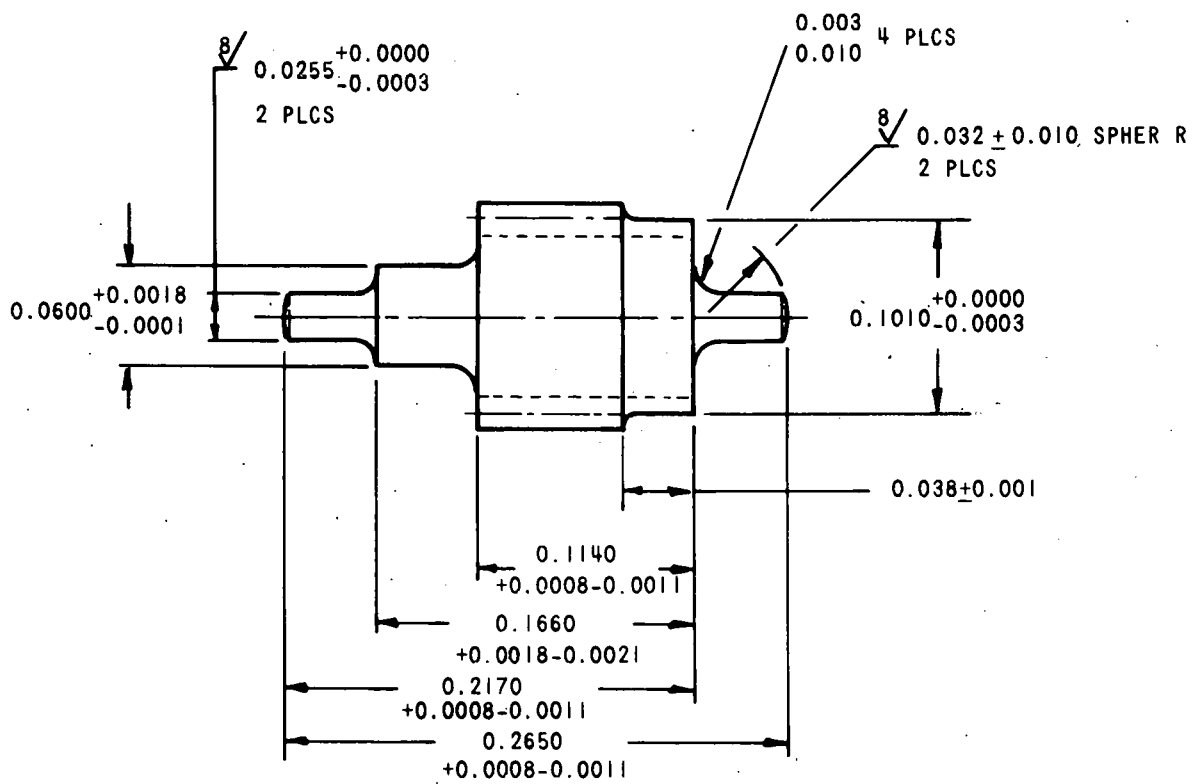
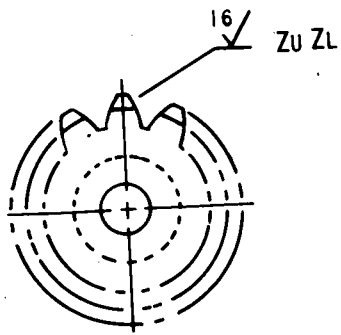


Figure A-2. Graphic Gear, Pinion

Appendix B

COMPOSITE CHARTS FROM FELLOWS NO. 4
REDLINER GEAR CHECKING MACHINE

INVOLUTE PROFILE CHARTS FROM FELLOWS 12-M
INVOLUTE MACHINE

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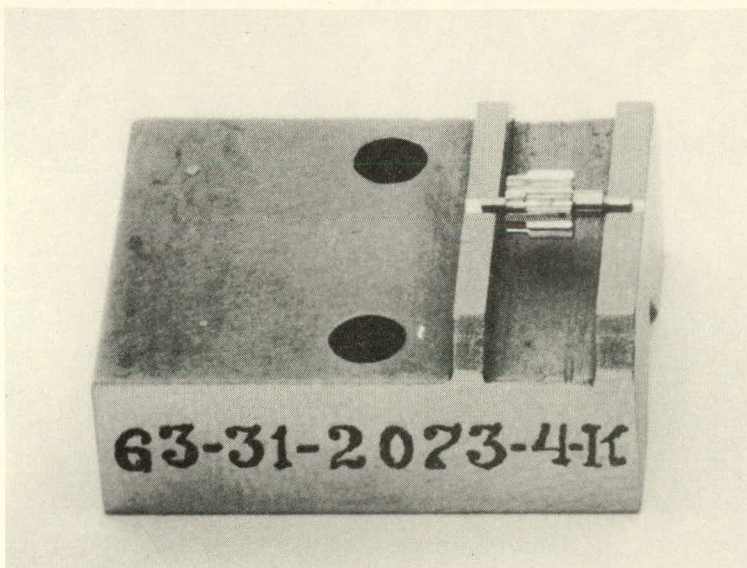
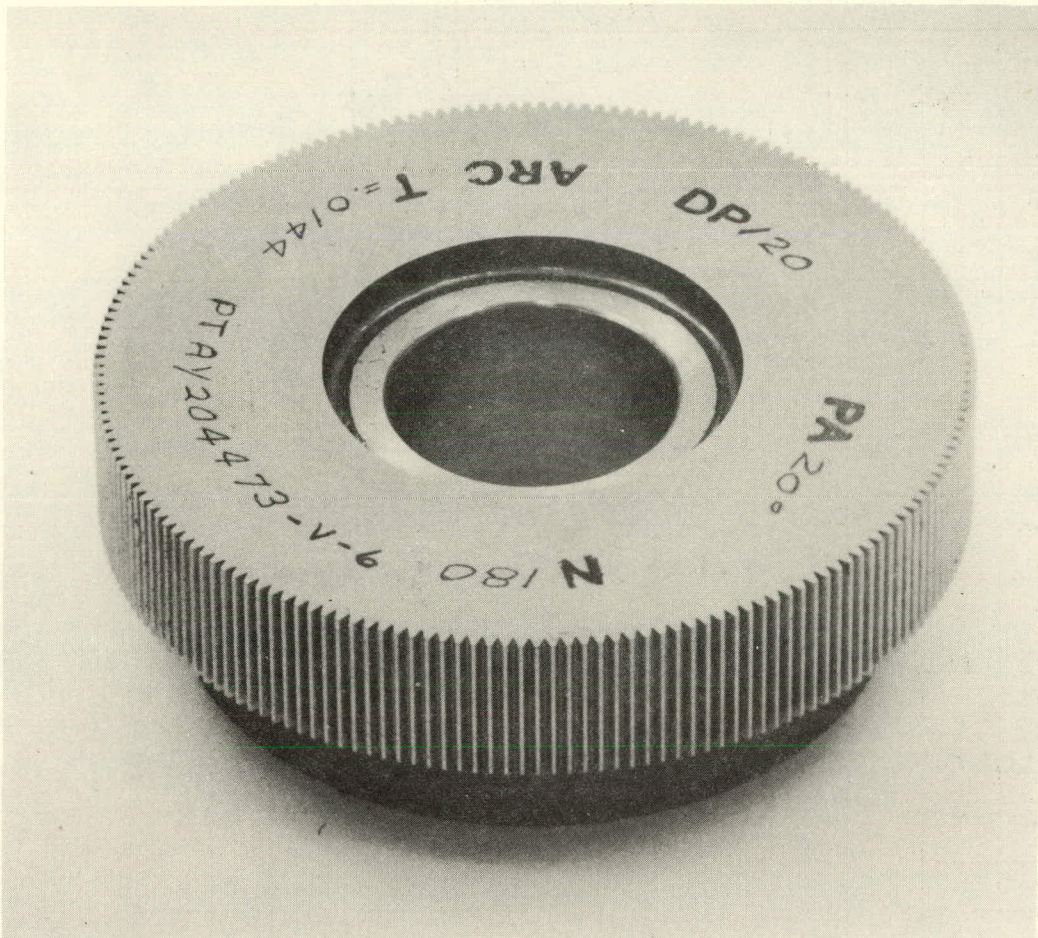


Figure B-1. Master Gear and Staging Fixture for Redliner Gear Checker

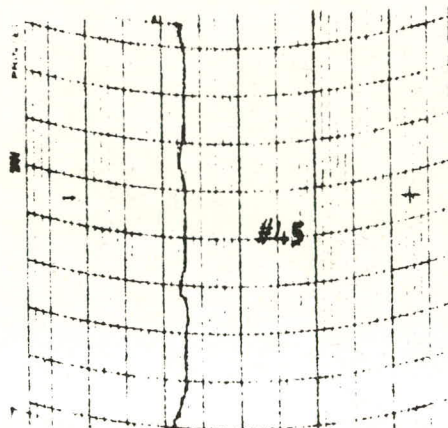
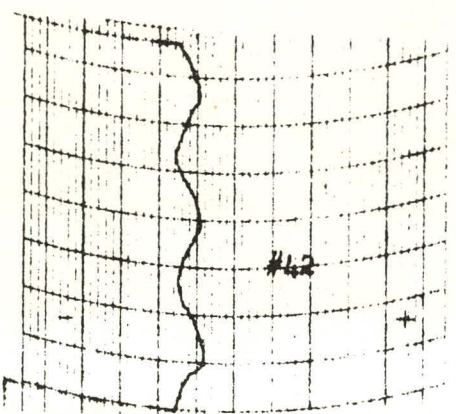
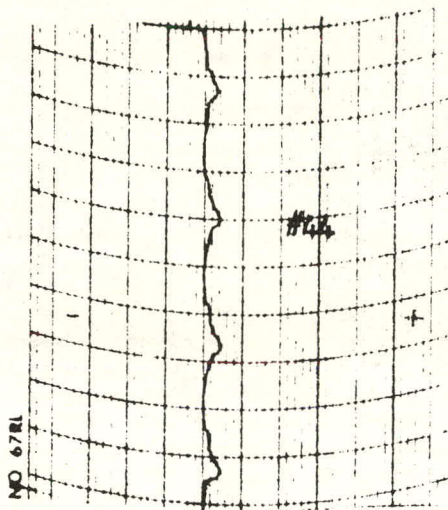
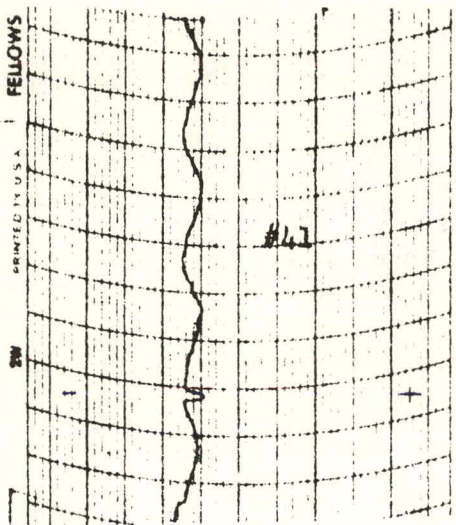
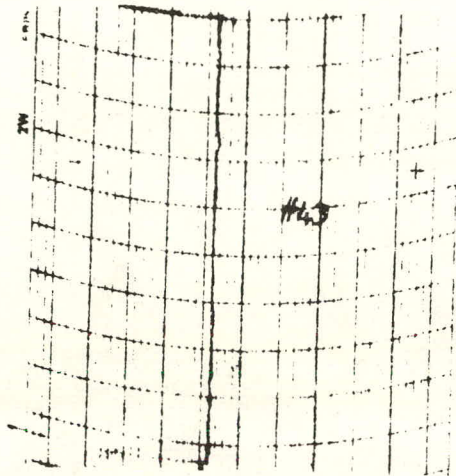
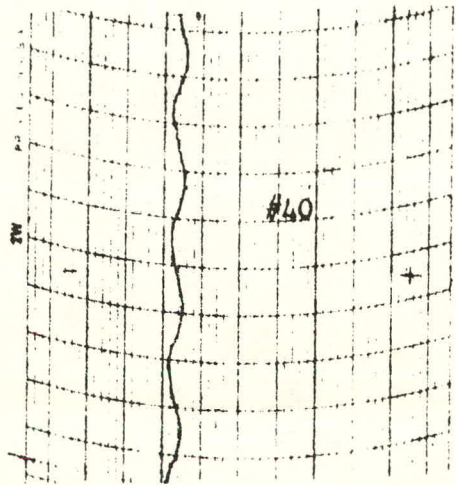


Figure B-2. Composite Readings Obtained at BKC on Fellows No. 4 Redliner Gear Checker

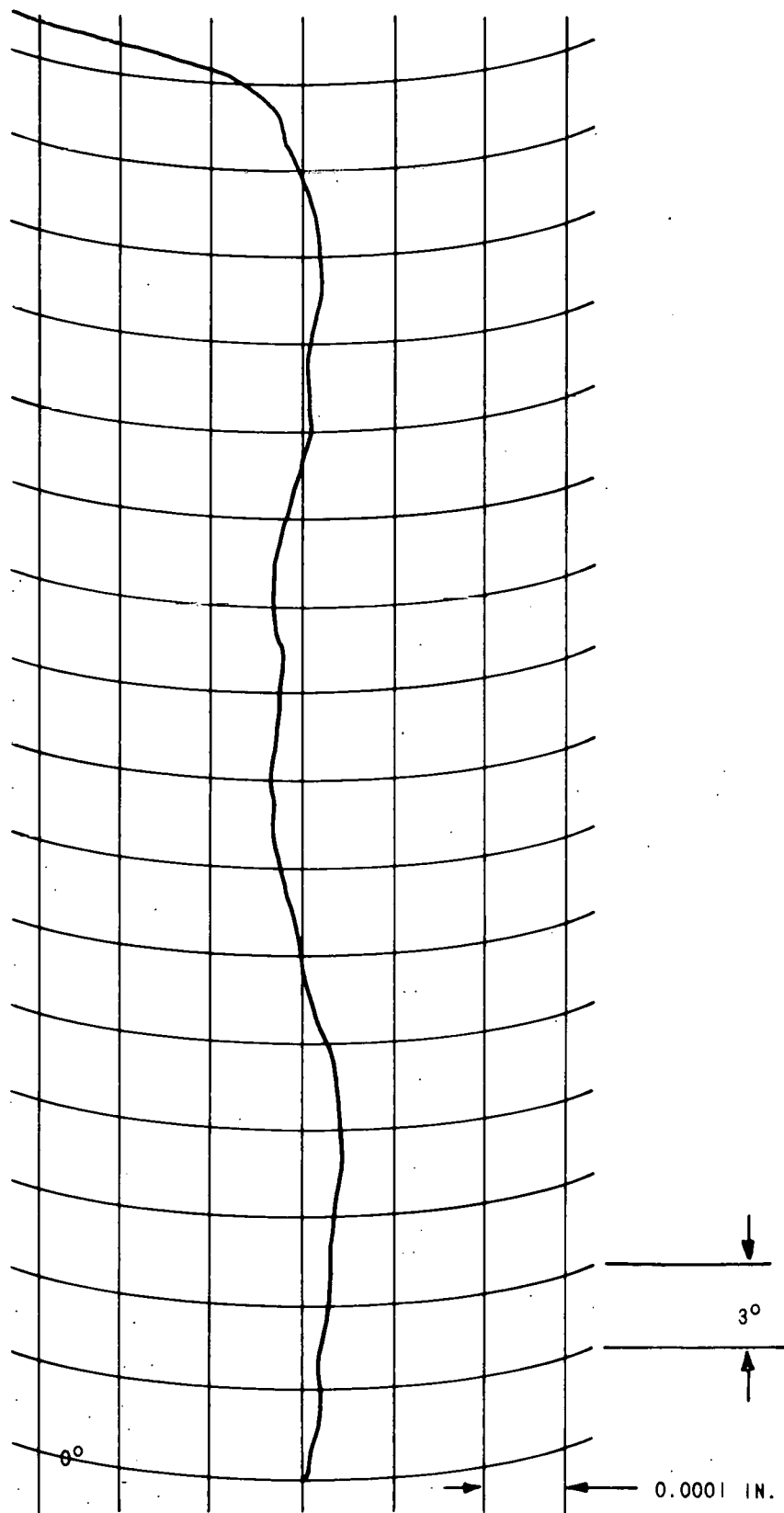


Figure B-3. Typical Involute Profile Recorded on Fellows 12-M Involute Machine

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Appendix C

WHEEL TRUING MECHANISM

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Appendix C

WHEEL TRUING MECHANISM

WHEEL TRUING

A rack form is threaded into the grinding wheel prior to the grinding operation. Since the Fellows No. 4 grinding machine has a separate self-contained truing mechanism, the wheel has to be removed from the grinding machine and mounted on the wheel truing spindle. The diamond dressing tool shown in Figure C-1 has the full form of the rack on it.

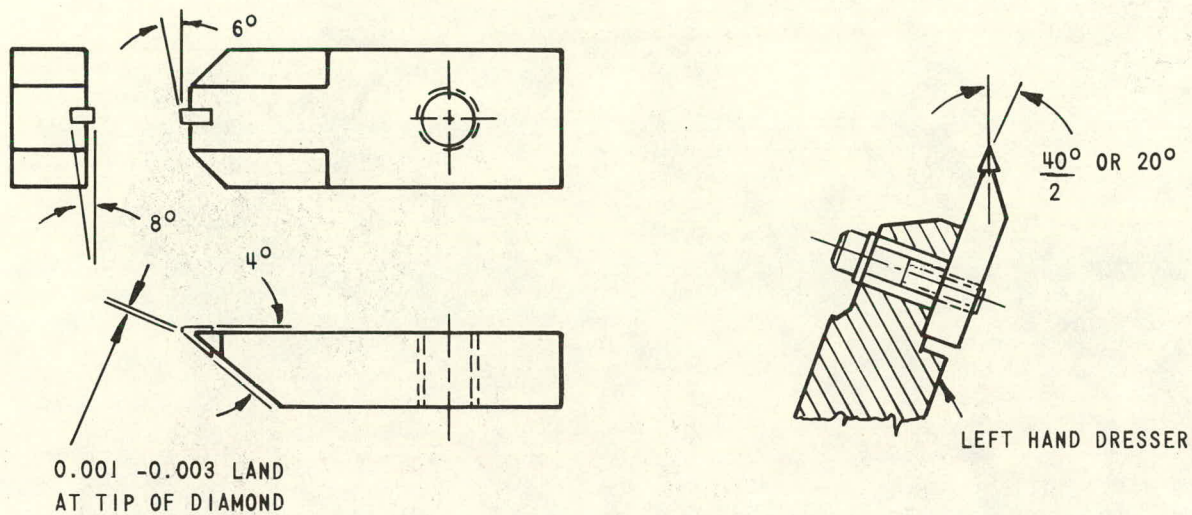


Figure C-1. Full Form Diamond Dressing Tool

The diamond tool is placed in the left-hand holder as shown in Figure C-2. The angle α (which sets the angle of the diamond in the proper attitude to the grinding wheel) is established by setting a spacing block between the dresser and the stop shown. The 0.9481 inch value for M is derived by using the formula

$$M = 3.937 \sin (40^\circ - \text{pressure angle}) - 0.3937.$$

The following set of change gears establishes the proper lead angle on the wheel. The lead angle is equal to the circular pitch of the gear to be ground (or $\frac{\pi}{120} = 0.0261$ inch per revolution of the wheel).

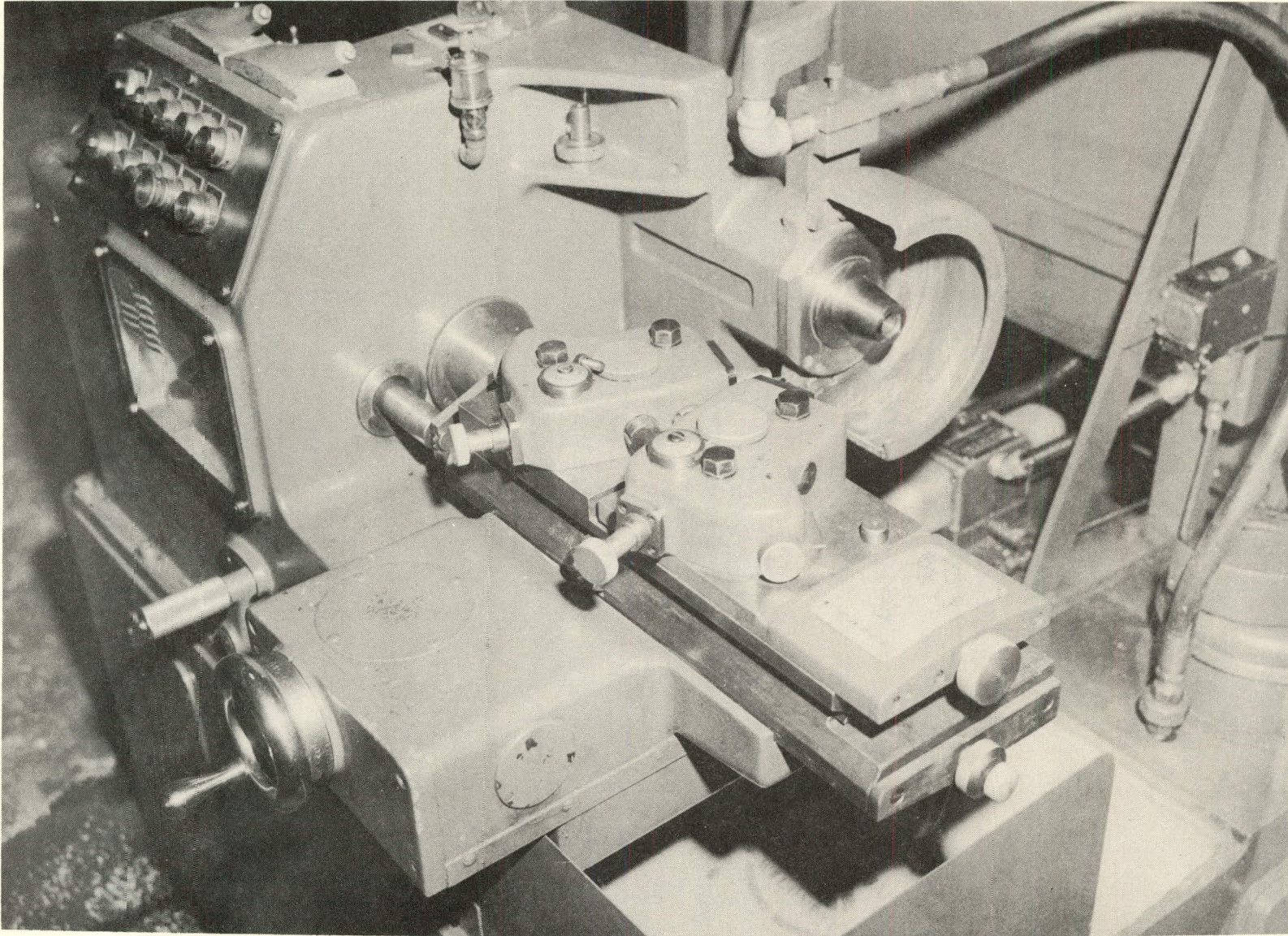
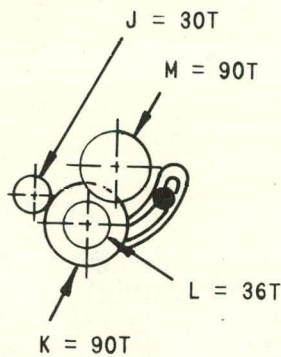


Figure C-2. Wheel Truing Attachment



The travel of the truing slide is set to overtravel the grinding wheel by about 1/4 inch on each end.

The whole depth of the tooth form plus clearance is calculated by the following formula

$$\frac{3.558}{DP} - 1.374 \times \text{flat on diamond}$$

The truing mechanism is turned on, which starts the grinding wheel rotation at the proper speed and the traverse of the truing slide. While the truing slide is traveling from right to left on its dressing stroke, the hand wheel is fed in until it touches the grinding wheel. This is the starting point for the threads on the grinding wheel and the dial setting on the micrometer drum is noted. The hand wheel is fed in 0.0005-inch during the return stroke of the truing slide until the 0.0255-inch full depth is obtained.

The grinding wheel is then removed from the truing mechanism and placed on the wheel head spindle of the machine.

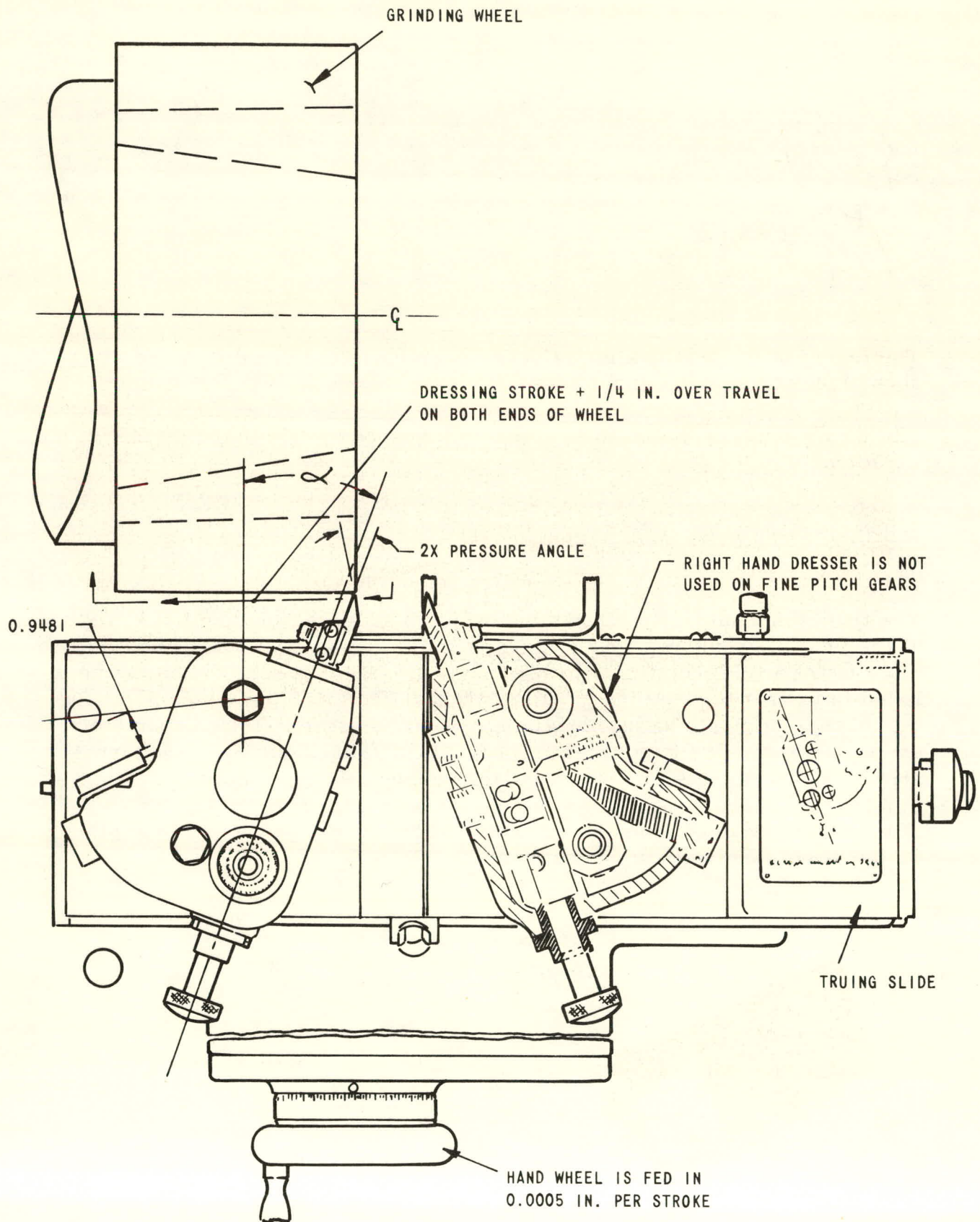


Figure C-3. Wheel Truing Device

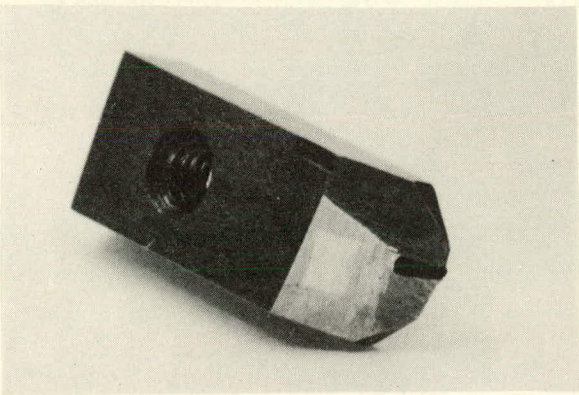


Figure C-4. Photograph of Diamond Dresser and Grinding Wheel