THE DEVELOPMENT & PRODUCTION OF THERMO-MECHANICALLY FORGED TOOL STEEL SPUR GEARS

by

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D. Townsend, Project Manager

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16. Abstract

A development program to establish the feasibility and applicability of high energy rate forging procedures to tool steel spur gears was performed. Included in the study were relatively standard forging procedures as well as a thermo-mechanical process termed ausforming.

The subject gear configuration utilized was essentially a standard spur gear having 28 teeth, a pitch diameter of 3.5 inches and a diametral pitch of 8. Initially it had been planned to use a high contact ratio gear design, however, a comprehensive evaluation indicated that severe forging problems would be encountered as a result of the extremely small teeth required by this type of design.

The forging studies were successful in achieving gear blanks having integrally formed teeth using both standard and thermo-mechanical forging procedures. In both cases, excess material in the critical gear tooth area was held to less than .015 inches over final machined dimensions. As a result, a production forging run utilizing both processes was performed. The resultant forgings were finish machined and forty gears (twenty each process) were delivered to NASA for test and evaluation.

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FOREWORD

The work described herein was performed by the Materials and Process Technology Laboratories, Aircraft Engine Group, General Electric Company under NASA Contract NAS3-15338. The technical program manager for NASA was Mr. D. Townsend, Bearing and Gearing Section NASA Lewis Research Center, Cleveland, Ohio.

The author would like to acknowledge the valuable assistance of Dr. E. J. Breznyak, Precision Metals Products, Inc., El Cajon, California, during the development portion of the high energy rate forging procedures. The contribution of Mr. D. Kroeger, MPTL, General Electric, who performed the metallurgical testing and handled the many peripheral activities inherent in this type of effort is also gratefully acknowledged.

1.0 SUMMARY

A development program to establish the feasibility and applicability of high energy rate forging procedures to tool steel spur gears was performed. Included in the study were relatively standard forging procedures as well as a thermo-mechanical process termed ausforming.

The subject gear configuration utilized was essentially a standard spur gear having 28 teeth, a pitch diameter of 3.5 inches and a diametral pitch of 8. Initially it had been planned to use a high contact ratio gear design, however, a comprehensive evaluation indicated that severe forging problems would be encountered as a result of the extremely small teeth required by this type of design.

The forging studies were successful in achieving gear blanks having integrally formed teeth using both standard and thermo-mechanical forging procedures. In both cases, excess material in the critical gear tooth area was held to less than .015 inches over final machined dimensions. As a result, a production forging run utilizing both processes was performed. The resultant forgings were finish machined and forty gears (twenty each process) were delivered to NASA for test and evaluation.

2.0 INTRODUCTION

The requirements being placed on advanced aircraft engines, gearboxes and helicopter transmissions with regard to weight reduction, increased service life and greater reliability also place an equally stringent demand on the gear material. The gearing in these applications is expected to carry higher loads, at higher temperatures and still provide increased life, low maintenance and high reliability. NASA Lewis Research Center, in an ongoing research effort is evaluating existing and developmental gear materials, in an attempt to define the mechanical properties of the existing materials and to establish the degree of improvement which can be expected from the newer materials. Within this overall effort, two areas of gear materials technology are being pursued. The first consists primarily of evaluating by life testing gear structural materials per se, while the second is aimed at improving gear material properties, by the introduction of special metal working techniques during the processing of these materials. It is within the scope of this latter area that the work discussed in this report was performed. The specific process utilized was a thermo-mechanical treatment termed "ausforming" which has been applied with considerable success in improving the rolling element fatigue characteristics of high speed bearing steels. Within the context of this report, the term ausforming will be used to describe a specific thermo-mechanical process which consisted of high energy rate forging of a Cr-Mo-V tool steel (AISI M-50) while subject material was in the meta-stable austenitic condition.

The primary objective of the work described herein and performed under NASA Contract NAS 3-15338 was to develop the ausforming procedures for a specific geometry spur gear, and to produce 20 such gears for delivery to and subsequent testing by NASA. Simultaneously, it was required that an equal number of parts be produced, also employing high-energy rate metal working procedures, except that these parts would be forged using more standard forging temperatures and practices. The intent, of the latter effort, was to provide test specimens for comparative evaluation against those produced by the thermo-mechanical forging procedure.

These objectives were successfully accomplished. The development activities performed in support of this work are summarized in the following sections of this report.

3.0 BACKGROUND

A great deal of importance is placed on the bending strength of aircraft gear teeth because a failure due to bending fatigue can often result in catastrophic damage to the entire gearbox or transmission. The designer establishes the gear tooth size (diametral pitch) on the basis of an allowable bending fatigue stress index number. These allowable stress index numbers, which establish limits for actual bending stresses, are often based upon static and dynamic test data, as well as field experience with a particular design and specific method of stress calculation.

At present, it does not appear that developmental gear materials will offer a significant improvement in gear tooth fatigue strength. Even if this were to be accomplished, it would have to be established that no detrimental effects on other equally critical gear material properties such as rolling element fatigue and wear resistance would be encountered. Thermo-mechanical processing was selected for evaluation as it offers a potential improvement in all of these vital material properties. The rationale for this reasoning is presented in the following paragraphs.

The thermomechanical process termed ausforming has been studied since 1954, when Lips and VanZuilen(1) first reported on work which they had been performing. Since then, a number of organizations both in this country (2, 3, 4) and abroad(5) have investigated the process. The application of ausforming to machine elements such as rolling-element bearings, was first reported by Bamberger in 1964(6). The material used in (Ref. 6) was M50. This material has the required metallurgical transformation characteristics for ausforming, and in addition is the prime material for current high-performance jet engine bearings. M50 was also chosen by NASA as the material of interest in the current gear study.

In the initial ausforming studies of M50, the material was evaluated at 40, 70, and 80 percent deformation, in order to establish the proper degree of working for maximum improvement under rolling-contact fatigue conditions. Testing was performed on the General Electric rolling-contact (RC) fatigue tester. This early work showed that approximately 75 to 80 percent of deformation was required in order to achieve the maximum benefit. This is illustrated in Figure 1. The Weibull curve for the 80-percent-worked material, which gave the greatest improvement in fatigue life, is shown in Figure 2 and is compared to the results obtained when testing bars made of the same heat of material but normally heat treated. The 90-percent confidence band for this latter series of tests indicates that the ausformed material constitutes a separate and superior population from the standard material, with an improvement of over 600 percent in the B_{10} life.

The next step was to evaluate the effects of ausforming in actual bearing tests. For this, a 35 mm bore single-row radial ball bearing was selected. Twenty such bearings, having ausformed inner rings and balls and standard heat-treated outer rings, were tested(7).

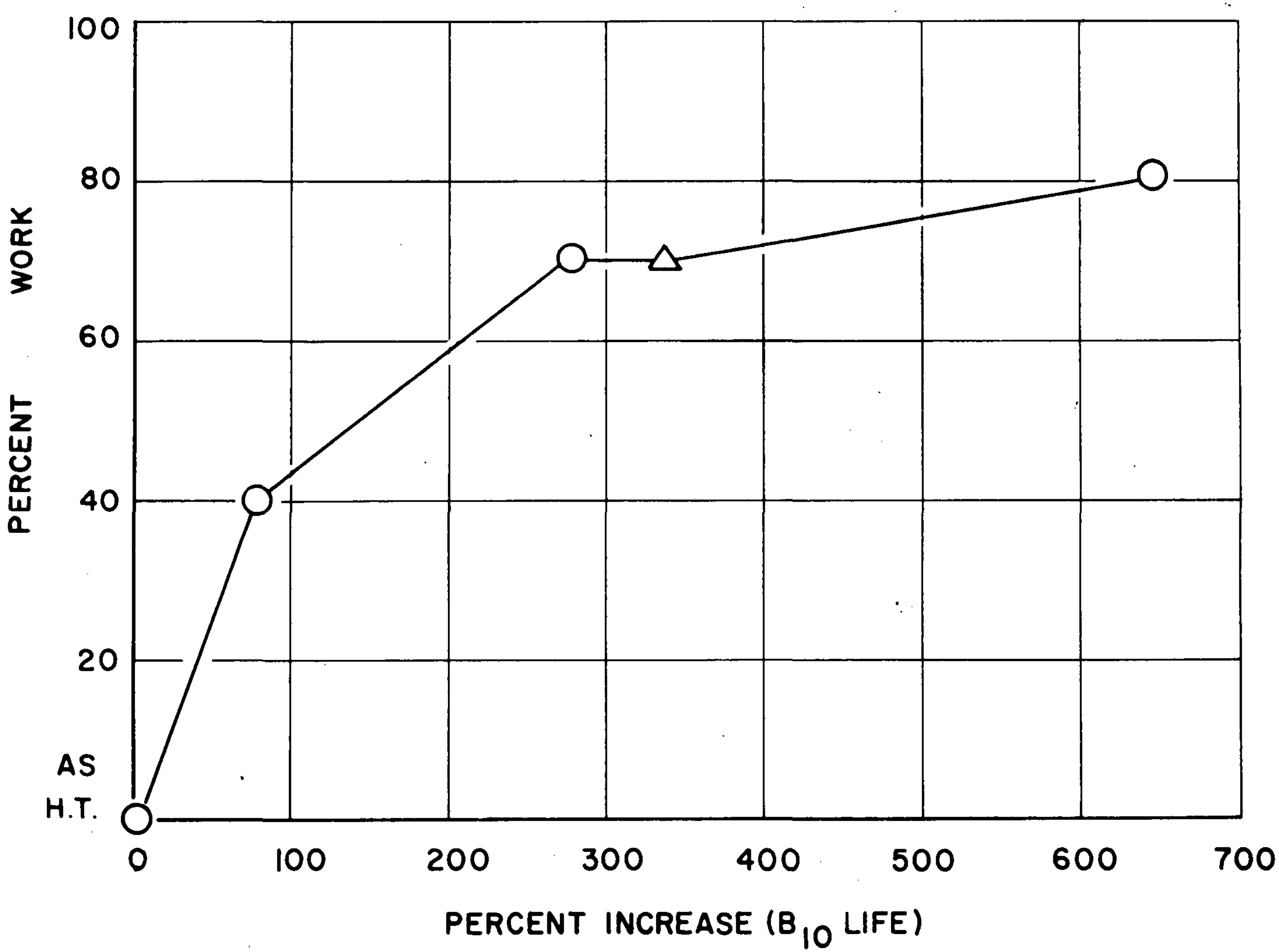


Figure 1 Percent Work (Deformation) as a Function of Bearing B_{10} Life

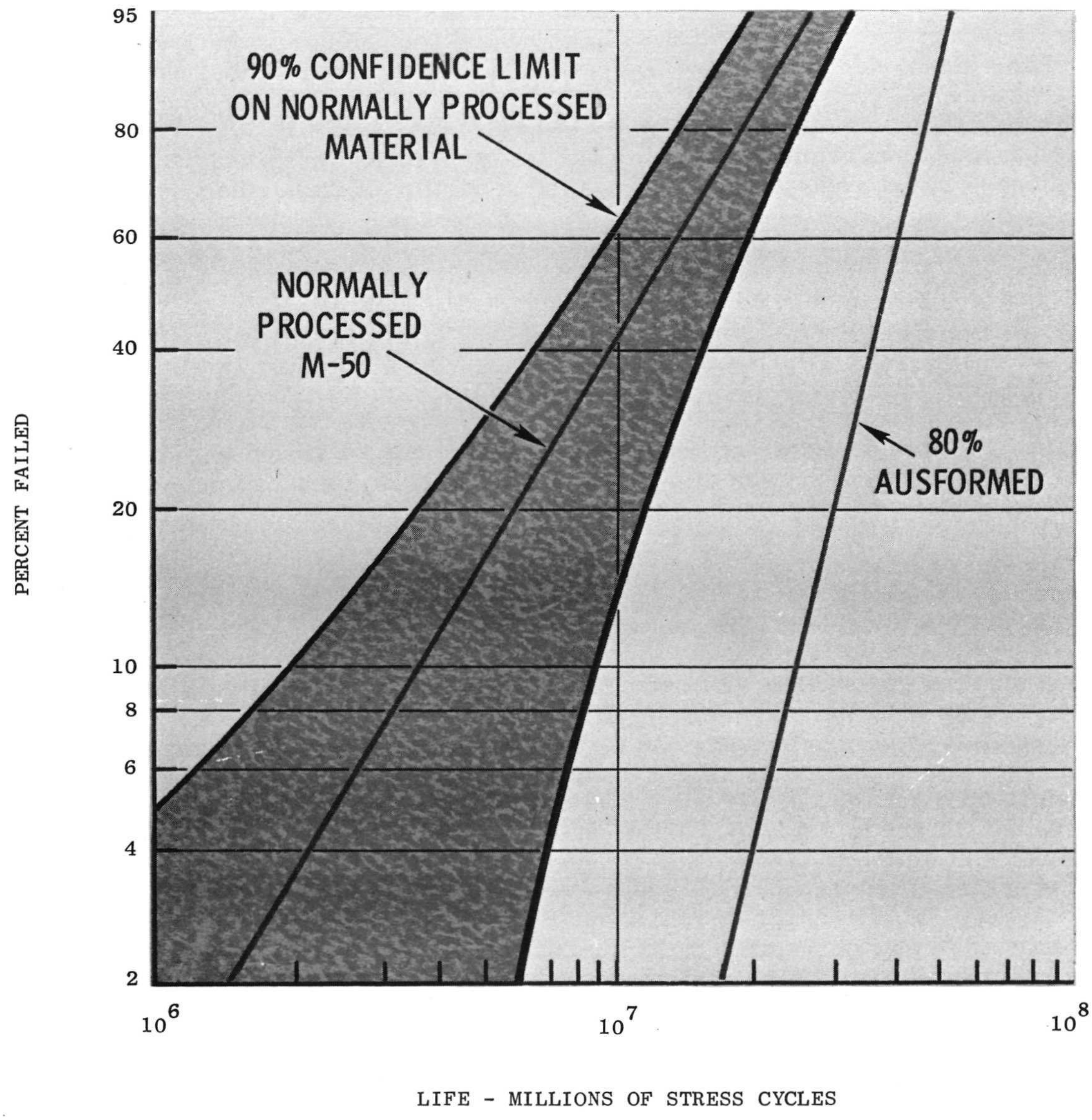


Figure 2 The Effect of Ausforming (80 Percent Work) on the Rolling Contact Fatigue Life of CVM M50

The test results of the ausformed bearings are presented in Figure 3. For reference, the data resulting from testing 27 additional bearings having all standard-heat-treated CVM M50 components are also shown. These latter bearings were identical to the ausformed bearings and were tested under the same conditions. The results confirmed the improvement in rolling-contact fatigue life predicted by the RC rig tests. Some of the ausformed balls produced for these bearings were independently evaluated by NASA(8), who also reported a significant improvement in fatigue life of these parts when compared to balls made from standard CVM M50 material.

General Electric has also performed considerable work in scaling up this process to larger diameter bearings(9). While the success here has not been as unequivocal as with the smaller sizes, directionally the results have demonstrated the potential life improvements possible with the ausforming process.

The application of ausforming to gears was therefore a logical progression in the utilization of thermomechanical processing to improve the reliability of these components.

The major causes of gear failure can be summarized as:

- Surface fatigue
- Adhesive wear
- Abrasive wear
- Bending fatigue

The different failure regimes are indicated in Figure 4, as a function of gear speed and torque. With the current knowledge of the beneficial effects of ausforming, it can be shown that each of these areas of gear distress will be aided by the ausforming process.

Surface fatigue (pitting) is akin to the rolling-element fatigue failures observed in bearings. Consequently, the data shown earlier on the effects of ausforming on rolling-element fatigue life are directly applicable to this gear failure mode.

Adhesive wear, or scoring, is generally caused by adhesive forces developed by the contact of two gear teeth when the oil film is insufficient to prevent contact of the mating surfaces. Metal asperities come into contact, and the high localized temperatures result in temporary welding of the two surfaces. As sliding continues, the welded surfaces separate, although the juncture does not necessarily take place at the original interface. The wear particles adhere to the surface to which they are transferred and eventually break loose. After repeated cycles of welding and fracture, the surface is badly deteriorated, and wear continues at an ever-accelerating rate.

Abrasive wear generally results when a hard surface slides over a softer surface. The harder material penetrates the surface of the softer material during the sliding action, scoring or otherwise damaging the softer surface. Abrasive wear may also occur when hard, foreign particles are trapped between the surfaces of the two softer materials. As a result, some of the debris caused by the adhesive wear can then result in abrasive wear.

Both of these wear processes are expected to be reduced by the use of ausformed material. This is based on results reported by the Ford Motor Company, which uses the ausforming process for tooling applications such as cold heading, rivet setting, piercing and extruding

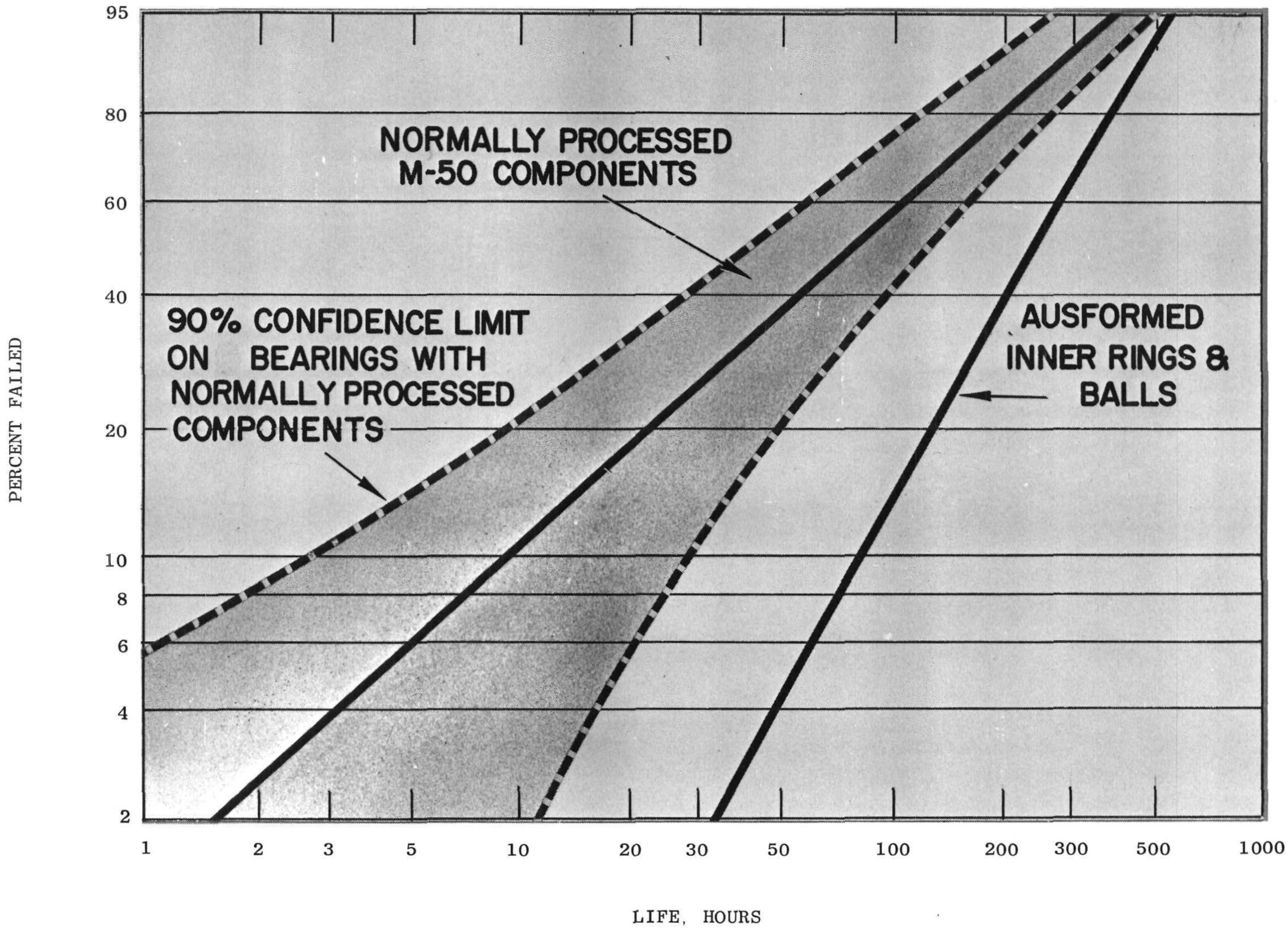


Figure 3 The Effect of Ausforming on the Fatigue Life of 35 MM, CVM M50 Radial Ball Bearings

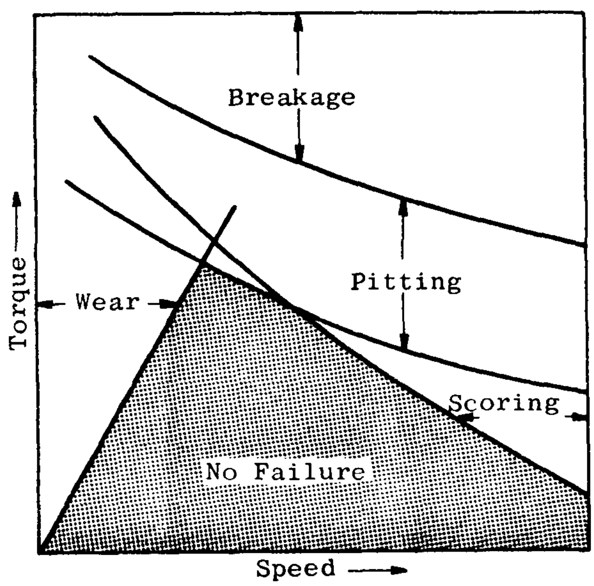


Figure 4 Gear Failure Characteristics

punches[10]. These processes generate wear situations similar to those experienced in the contact surfaces of gears. Ford has reported increases in life of 300 to 500 percent when ausformed tools were used. This is shown in the following listing:

Tool	No. of Pieces Formed per Tool
• Rivet head former	
Regular AISI T5	200,000
Ausformed H11	600,000
• Hex head bolt punch	
Regular AISI T5	30,000
Ausformed H11	70,000
• Hex head bolt punch	
Regular AISI T5	50,000
Ausformed Vasco MA	160,000
• Piercing and extruding punch	
Regular M2	77,000
Ausformed H11	120,000

One of the most significant applications was the use of ausformed H13 steel for a hot shearing punch in one of the Ford plants. This punch was used to pierce 1-inch diameter holes in hot-forged blanks for differential side gears. The conventional punch lasted about 14,000 pieces on the average. The ausformed punches, produced by vertical extrusion, pierced an average of 26,000 gear blanks before losing dimensional accuracy.

The improved wear resistance of the ausformed materials can be explained on the basis of the metallurgical structure generated by the ausforming process. One of the primary contributing factors to the extended life of the ausformed material is the reduction in size of the carbide particles, as well as their more uniform dispersion throughout the structure. The benefit of having small, uniformly dispersed carbides is that these particles will increase the resistance to wear while lessening the severity of dislocation pileups and, hence, the stress concentrations which accelerate crack initiation or propagation. The latter observation also applies directly to the fourth failure mode. A great deal of importance is placed on the bending strength of aircraft gear teeth, because a failure due to bending fatigue can cause serious damage to the entire gearbox or transmission.

In this area of concern, ausforming should be most beneficial. Lemanski[11], reporting on single-tooth, nonrotating bending fatigue tests of typically-sized aircraft quality gears made of M50, states that "The M50 test gears indicated that the material does not resist crack propagation, in comparison to the other two materials tested." While these conclusions are not substantiated by work performed at General Electric[12], ausforming should significantly reduce such a problem because of its increased resistance to crack initiation or propagation and its improved fracture-toughness characteristic. Borik, et al[13], as well as McEvily and Bush[14], have commented on this very fact in that they believe the resistance to crack propagation of ausformed steel is one of the main factors contributing to the high fatigue strength of these steels.

4.0 PROGRAM SCOPE

The program was segmented into four major technical tasks. These were as follows:

4.1 TASK I - GEAR DESIGN

In this task, a high contact ratio type spur gear, using a pitch diameter and center distance of 3.500 inches was to be designed, having a diametral pitch which would produce a combination of high tooth strength and good surface load capacity.

4.2 TASK II - STANDARD GEAR FORGINGS

The manufacturing technique for high energy rate forging of M50 gear preforms having integrally formed teeth was to be developed. Following this, sufficient preforms were to be produced to net 20 finish machined gears. The necessary physical and metallurgical evaluation of the forged preforms was to be conducted to assure the structural and dimensional integrity of the parts.

Since, at the outset of the program, no firm assurance could be given that M50 could be forged as planned (i.e., with integral gear teeth) a back-up forging program was included which consisted of forging a plain gear blank (no teeth). It was reasoned that this could be used to hob out a gear if so required, although the grain flow pattern would not be as desirable as in a gear having integrally forged teeth.

4.3 TASK III - AUSFORMED GEAR FORGINGS

The manufacturing technique for the high energy rate thermomechanical forging of M50 gear preforms, having integrally formed teeth was to be developed. Following this, sufficient preforms were to be produced to net 20 finish machined gears. As was the case with the parts in Task II, the necessary physical and metallurgical controls were to be exercised to assure sound parts. Additionally and similar to Task II, blank forgings were also to be produced, in the event the ausforming of integral teeth preforms proved to be physically, and/or in this case economically, unfeasible.

4.4 TASK IV - FINISH MACHINING AND INSPECTION

Following the forging of the standard and thermomechanically forged preforms, twenty each gears were to be finish machined, inspected to conform to the metallurgical and dimensional tolerances specified by NASA, and delivered to NASA for test and evaluation.

5.0 GEAR DESIGN

The initial intent was to design and manufacture a high contact ratio gear. These gears are characterized by a tooth form which has long thin (fine-pitched) teeth. As a result of this configuration, the tooth load is distributed between three pairs of teeth during the entrance phase of engagement, two pairs in contact at the pitch point, and three pairs during the exit phase. This contrasts to a standard involute gear, where the load distribution is shared between two pairs of teeth during the entrance phase, one pair at the pitch point, and two pairs during the exit phase.

The reported advantages of high-contact-ratio gears include the following:

- Increased surface contact capacity
- Increased bending strength capacity
- Smoother tooth action
- Reduced noise level
- Reduced sensitivity to profile and spacing errors
- Improved mesh efficiency

The design of the specific high contact ratio gear for use in subject program was subcontracted to the Boeing Co., Vertol Division because of their past experience with this type of gear configuration and the ready availability of computer programs to aid in the design of the gear. The result of the Boeing study and their recommended design is included in this report as Appendix I.

In reviewing the appended data it may be seen that the gear recommended by Boeing had a profile contact ratio of approximately 2.1, a diametral pitch of 11.14286, and a 39 tooth complement. This combination of diametral pitch and overall gear diameter results in a gear having extremely small, thin teeth. The individual teeth have a total height of only 0.25 inch with top land surfaces somewhat less than .035 inch. This miniscule tooth configuration posed a serious problem from the standpoint of obtaining reproducible and sound high energy rate forgings using standard forging techniques,and a correspondingly greater degree of difficulty with a thermomechanically processed part. This matter was reviewed in considerable detail with the technical personnel, who would be performing the actual forging operations as well as with General Electric forging experts. After lengthy discussions and a thorough evaluation of every possible means to utilize the high contact ratio tooth configuration it was the unanimous decision of all involved that subject tooth configuration was not practical for the intended purpose. Consequently it was recommended to NASA that a more standard gear configuration be used for this program, in order to evaluate the effectiveness of the high energy rate forging and thermomechanical working process on M50 gear materials. The gear design recommended was essentially the modified Ryder gear type, currently used by NASA in their in-house gear research program. This design is shown in Figure 5 and the pertinent dimensions and specifications of the gear are presented in the following tabulation.

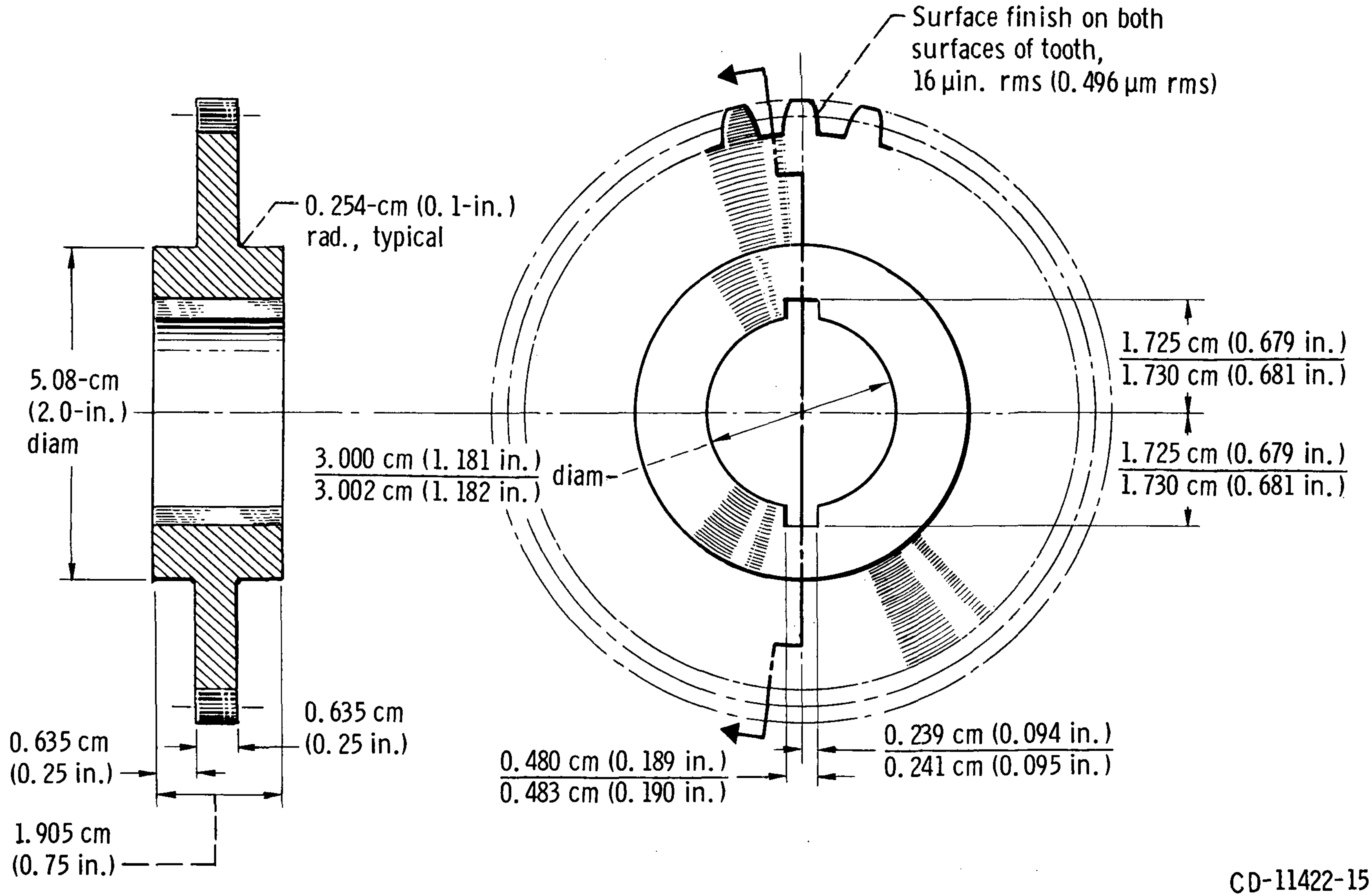


Figure 5 NASA Design Spur Gear

Number of teeth - 28
Diametral pitch - 8
Pressure angle - 20°
Pitch diameter - 3.500 inches
Outside diameter - 3.75 inches
Addendum - .125 inches
Whole depth - .300 inches
Circular pitch - .3927 inches
Chordal tooth thickness - .191 inches

6.0 GEAR MATERIAL

The material for the forging and ausforming studies, as well as for the subsequent production of 20 forged and 20 ausformed gears, was a high-speed tool steel manufactured by a consumable vacuum melting (CVM) process. This tool steel, M50, is currently used as the major structural material for main engine bearings by U.S. jet engine manufacturers. Its use as a gearing material has been limited, although the General Electric Company has performed high-temperature Ryder gear tests on the material[12]. As shown in Table 1, the M50 shows some superiority in load carrying capacity when compared with premium gear materials such as Super Nitralloy.

The CVM M50 used in the current study was purchased to General Electric specification B50TF103 which meets or exceeds AMS 6490A. The chemistry and other pertinent details of the specific heat of material used is presented in Table 2.

TABLE 1

High Temperature Load - Carrying Capacity Determinations for Two Gear Materials

Test No.	Load-Carrying Capacity, lb/in. A Side	B Side	Avg.
		M-50 Test Gears	
M-1	2920	3500	3210
M-2	3680	3820	3750
M-3	4020	3720	3870
			3610
		Super Nitralloy Test Gears	
N-1	3540	3290	3420
N-2	3110	3130	3120
N-3	2860	2910	2890
			3140

Test Conditions:

Test Oil - MIL-L-23699	
Test gear temperature, °F	425
Test oil-in temperature, °F	400
Test oil flow, ml/min	270
Speed, rpm	10,000

Gear Data

Super Nitralloy

Diametral pitch	8
Pitch diameter, in.	3.500
Face width, narrow gear, in.	0.250
Face width, wide gear, in.	0.375
Number of teeth	28
Pressure angle, degree	22.5
Material, G.E. Spec.	C50TF5
Case hardness, Rockwell N15	92 min.
Case thickness, in.	.018 to .024
Core hardness, Rockwell C	39-40

M-50

Diametral pitch	8
Pitch diameter, in.	3.500
Face width, narrow gear, in.	0.250
Face width, wide gear, in.	0.375
Number of teeth	28
Pressure angle, degree	22.5

TABLE 2

Chemical & J-K Rating of CVM M50
used in Gear Forging Program

Vendor: Carpenter Steel Co.

Heat: #89660

Chemistry:

C	Mn	Si	P	S	Cr	Ni	Mo	Cu	V	Co	W
.80	.24	.22	.006	.005	3.98	.07	4.18	.06	.98	.05	.04

Average Jerkontoret Inclusion Rating

A		B		C		D	
Thin	Thick	Thin	Thick	Thin	Thick	Thin	Thick
0	0	0	0	0	0	1	0

Magnaflux

Frequency - 0, Sensitivity - 0

Fracture Cleanliness

Tested and approved

Hardenability

Rc 64

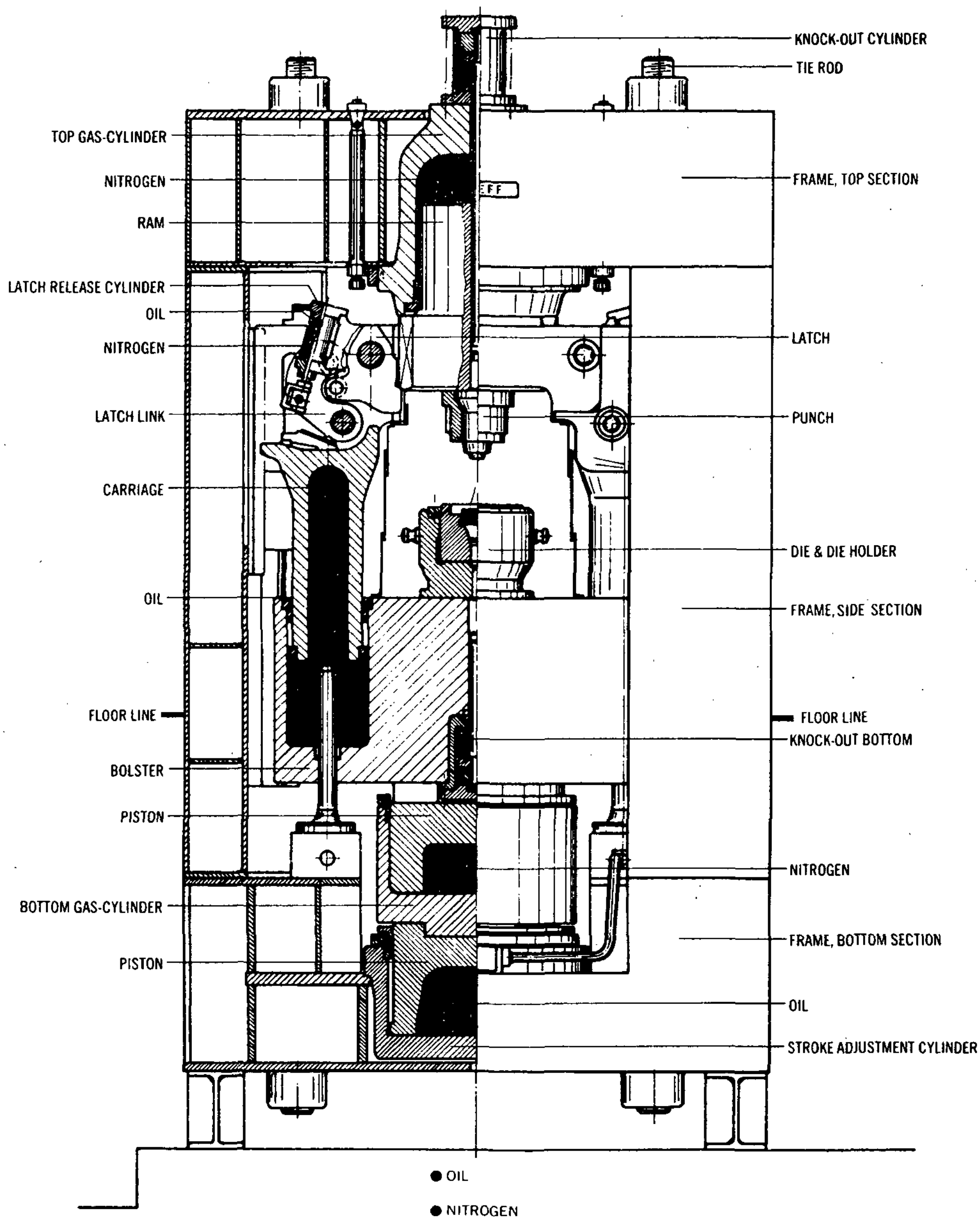
7.0 HIGH ENERGY RATE FORGING FACILITIES

The forging development was to be carried out by using high energy rate equipment. It was recognized at the outset of this program that such forming of gears had been attempted in the past[15] although in the referenced work, the materials were standard low carbon steels (AMS 6265) which, after forming were carburized per the usual practices. Since two processes were therefore combined, it was difficult to assess the effects of high-energy-rate forming only on the operational characteristics of the gears.

In the current program, a controlled-energy-flow forming technique (CEFF) was utilized for the ausforming, as well as for the normal forging of the gears. This high-velocity metalworking procedure has been a production process for the past several years by the Precision Metals Products Company, El Cajon, California[16].

The equipment used is shown schematically in Figure 6 and illustrated in Figure 7. The CEFF equipment uses the counter-blow concept, but employs two independent cylinders to accomplish this action. Nitrogen is pressurized at maximum energy to 1400 psi. Provision is made to operate the machine with dissimilar pressures in the two cylinders. This allows the balancing of the system to provide equal momentum at impact, which, in turn, provides efficient and rapid transfer of energy to the tooling and to the work piece. A trigger system, with a hydromechanical lock for the upper ram and lower bolster, synchronizes the simultaneous release of both parts of the tool. After firing, the latch system separates the tools to their starting positions in conjunction with ancillary pressure cylinders. The energy can be established by regulating the cylinder pressure and by adjusting the forging stroke. The combinations of stroke and cylinder pressures that may be used to obtain equivalent pressures are given in the theoretical curves shown in Figure 8.

Ready for Impact



The nitrogen in the upper and lower gas chambers has been compressed to the point required to produce the desired amount of energy. The hydraulic oil in the two carriage cylinders is pressurized to keep the ram and the bolster separated while the machine is awaiting activation. As a safety measure, the latch system is self-locking for the prevention of accidental cycling.

Figure 6 Schematic of Controlled Energy Flow Forming (CEFF) High Energy Rate Forging Equipment

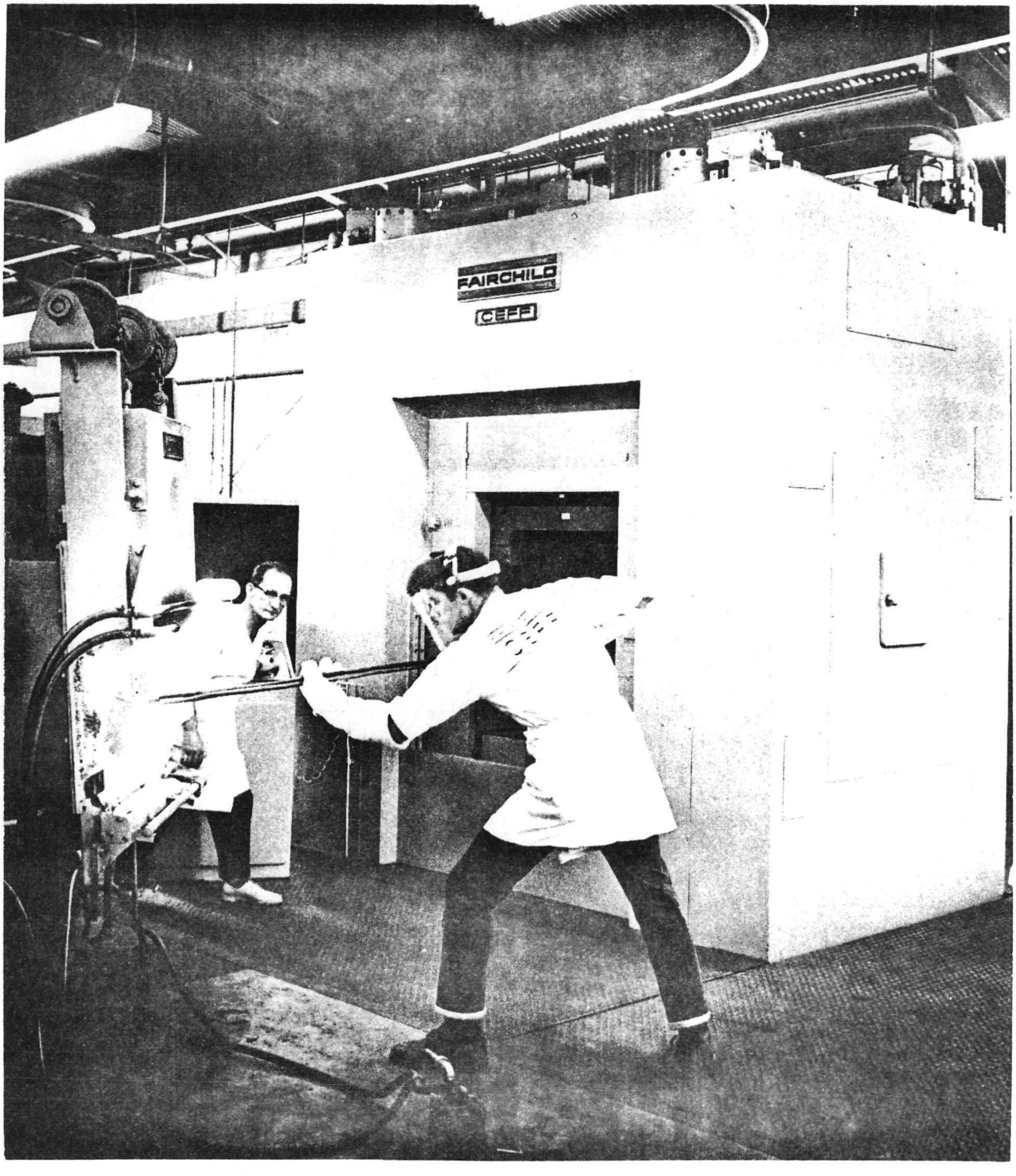


Figure 7 CEFF Machine in Operation

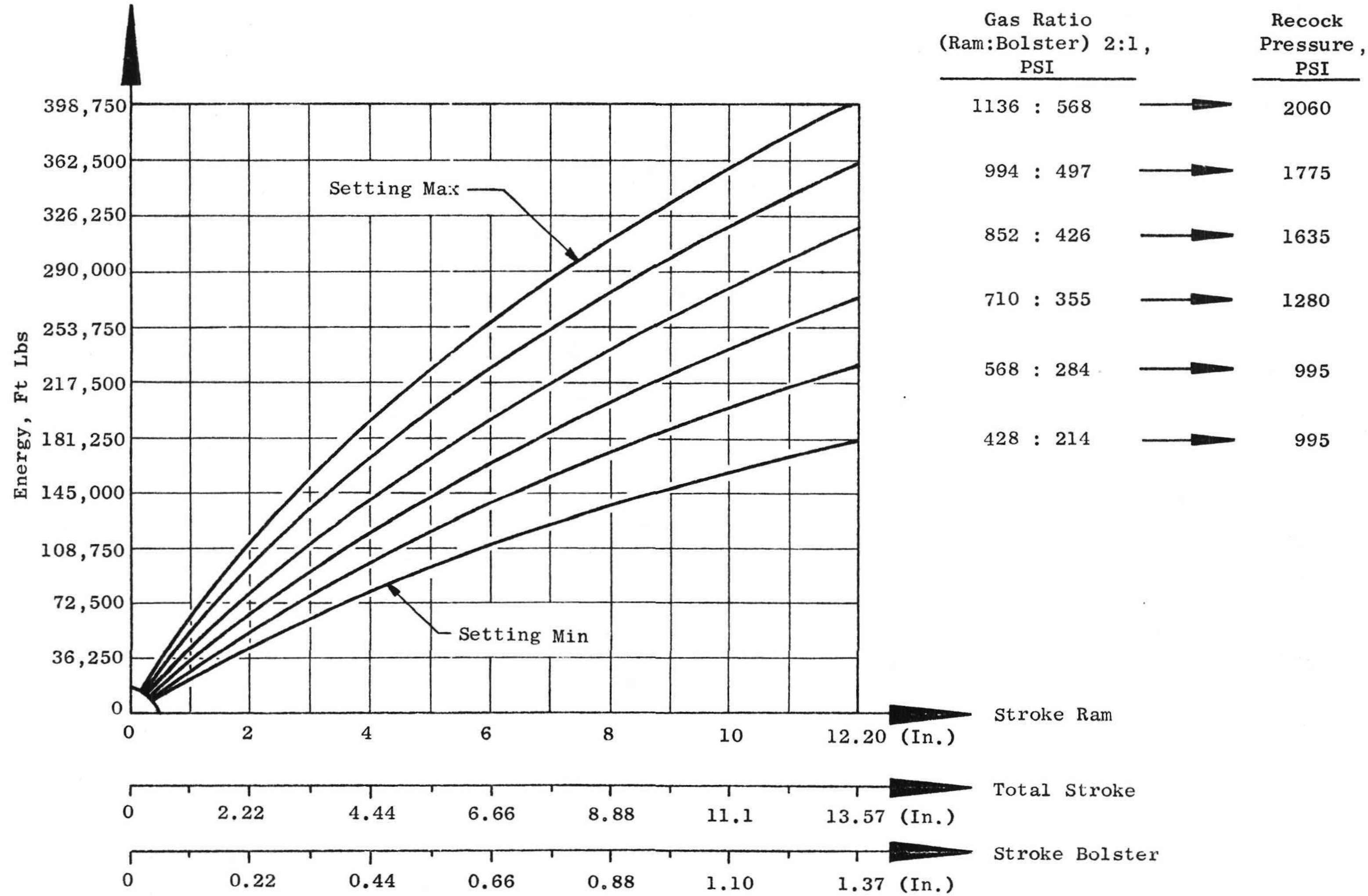


Figure 8 CEFF Energy Curves.

8.0 FORGING OF GEAR BLANKS

As with any other developmental metal-working process, a number of iterations were required before the optimum sequence of forging was established. Rather than detail all of the numerous minor corrections and adjustments made in thermal cycling, die and preform design, material handling, etc., a general summary will be presented designed to highlight the major accomplishments. Also, for clarity, each component will be discussed separately, recognizing that in actual practice, the parts were not handled in this manner.

8.1 GEAR BLANK - NO TEETH - STANDARD FORGING

This part was a back-up in the event the integral tooth gear blank could not be successfully forged. Due to its relatively simple shape, illustrated in Figures 9 and 10, no undue difficulties were encountered. A lack-of-fill condition initially experienced was remedied easily by increasing the forging energy.

The actual forging sequence consisted of the following cycle:

Preheat: 1500°F/30 min.

Forging Temp: 2000°F ± 25

(Held in endothermic furnace, dew point of 10°F ± 5°F, 30 minutes prior to forging)

Forge:

Still Air Cool to Room Temperature

Anneal: 1500°F/4 Hr. - Slow furnace cool to 1000°F - Air Cool to Room Temperature

8.2 GEAR BLANK - NO TEETH - AUSFORMED

This part was also a back-up in case the integrally ausformed teeth forging proved to be not feasible. Because of the more involved ausforming procedure and higher forging energy required, some minor problems were encountered although these were readily resolved. As a point of comparison, the energy required to ausforge these parts was approximately 25 percent greater than that needed to forge the blanks at the normal temperature. The ausforming cycle was as follows:

Preheat 1500°F/30 min
Austenitize 2075°F ± 25°F/30 min
Rapid Air Cool to 1500°F
Place into 1475°F stabilizing furnace
Hold for 5 min at 1475°F

Forge
Oil quench to 150°F
Air cool to R.T.
Stress relief at 950°F/2Hrs

Typical forgings made by this procedure are shown in Figures 11 and 12.

Figure 9 High Energy Rate Forged M-50 Gear Blanks - Standard Forging Cycle

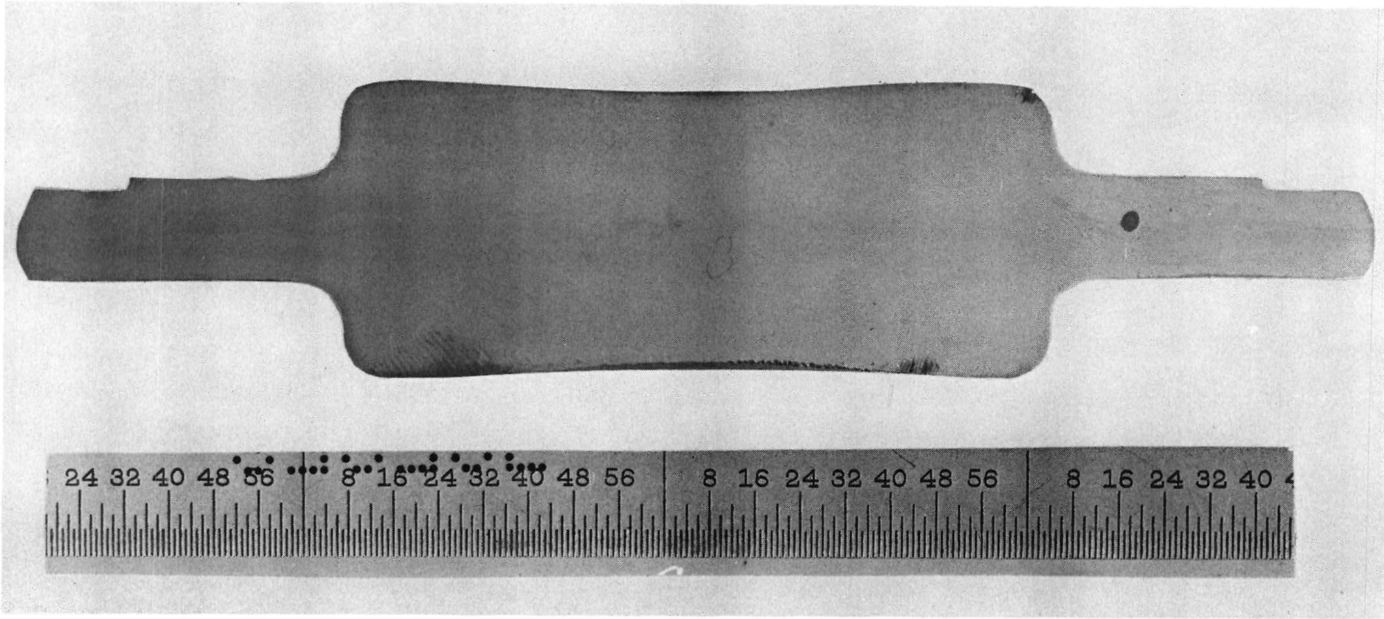


Figure 10 Cross Section Through Standard Forged M-50 Gear Blank

Figure 11 High Energy Rate Ausforged M 50 Gear Blank

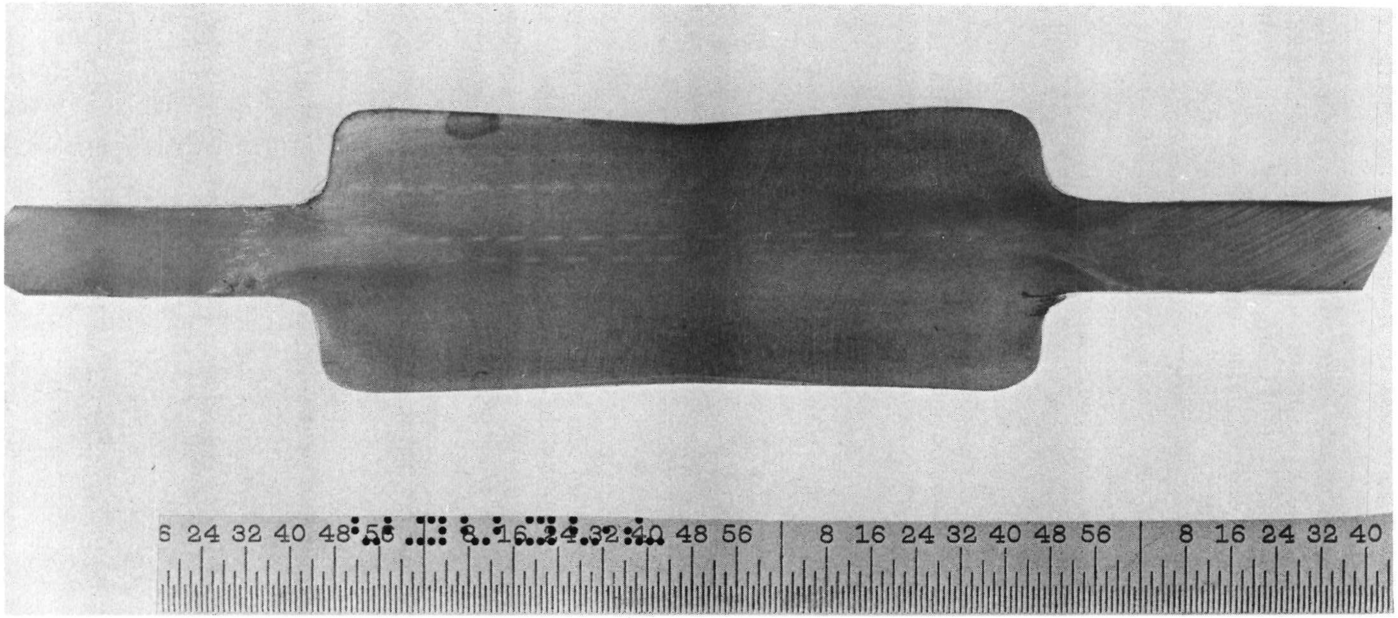


Figure 12   Cross Section Through Ausforged M-50 Gear Blank

8.3 INTEGRALLY FORGED TEETH-STANDARD FORGING

The die inserts used for these forgings are shown in Figure 13. The initial two forging trials resulted in a considerable lack-of-fill condition at the outer gear tooth periphery which was partially remedied by increasing the volume of the forging preforms shown in Figure 14. After several other minor changes including an increase in the forging temperatures to 2050°F acceptable parts were produced during the fourth forging trial.

A number of parts forged during this run were sectioned radially in order to obtain a better measure of the tooth profile and the overall material envelope. Comparator measurements showed that the configuration of the as forged tooth was nearly perfect, matching the forging drawing, (and gear drawing) almost exactly. However, as shown in Table 3 the actual tooth measurements were a cause of concern.

To better relate these measurements, a section of the forging drawing is shown in Figure 15. The shaded area in subject drawing indicates the excess stock which was considered necessary to allow for cleanup to the final tooth dimensions. Generally, this excess material was planned to be between .010 to .015 inches.

The dimensions given in Table I are relative to the final machined tooth profile. These indicated that on the tooth surfaces, the actual excess material was only about .003 to .005 inches, which was considered marginal in terms of material available for complete cleanup. The outside diameter as well as the base radius dimensions were undersize by .004 to .0075 inches.

Neither of these conditions was considered serious as only a minimal die modification was required to rectify this problem. The reason for the dimensional deviations from the forging print were attributed to the fact that the die dimensions were based on calculated metal shrinkage from the ausforming temperature range (1200-1500°F). Since the subject gear was forged at 2000°F, a correspondingly greater amount of shrinkage was experienced. In other critical areas such as root radii and width of tooth top land, the as forged gear was well within acceptable dimensional variances.

Following an additional die modification and a slight change in preform size, dimensionally acceptable gear forgings were produced. These are shown in Figures 16 through 20. Dimensionally, these parts were within the specifications which required the material envelope not to exceed .015 inches per side on the gear teeth.

8.4 INTEGRALLY FORGED TEETH - AUSFORMED

These parts, as anticipated proved to be considerably more difficult to produce. The initial forging trial was performed on a Model HE-10 CEFF machine which has a maximum energy output of 75,000 foot lbs. This unit had been adequate for the production of both blank gear forgings (Items 8.1, 8.2) as well as the standard forged integral tooth gear (Item 8.3). At the 1475°F ausforming temperature however, the HE-10 unit did not have sufficient capacity as shown by the forgings illustrated in Figure 21. This photograph clearly demonstrates the minimal movement of the M50 material into the gear tooth configuration of the die. It was therefore decided to adapt the tooling to the larger HE-55 CEFF machine which has a capacity of 400,000 foot lbs. This was done and the first forging trial was still not encouraging despite a considerably higher forging energy. This is illustrated by the parts shown in Figure 22. In reviewing the operation it was apparent that die closure had taken place, causing

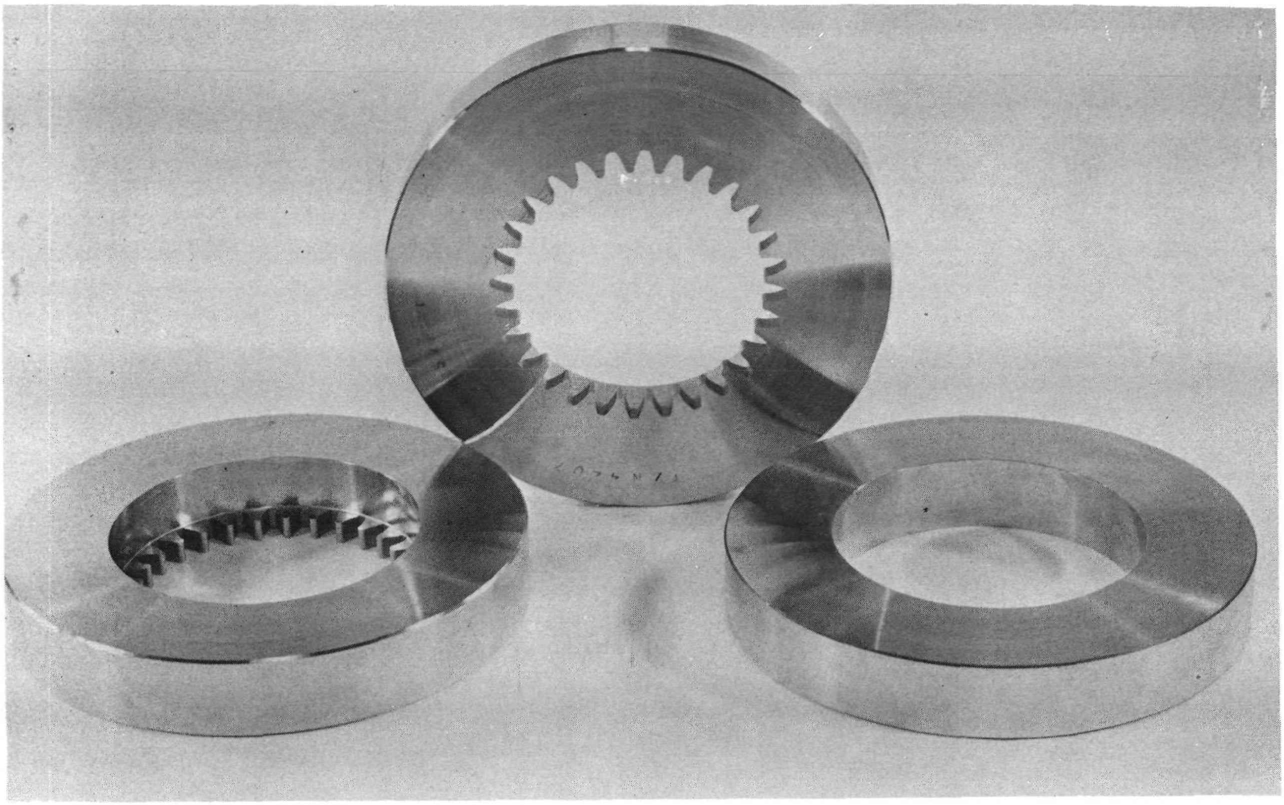


Figure 13 Tooling Inserts Utilized For Forging Gear Blanks With and Without Teeth

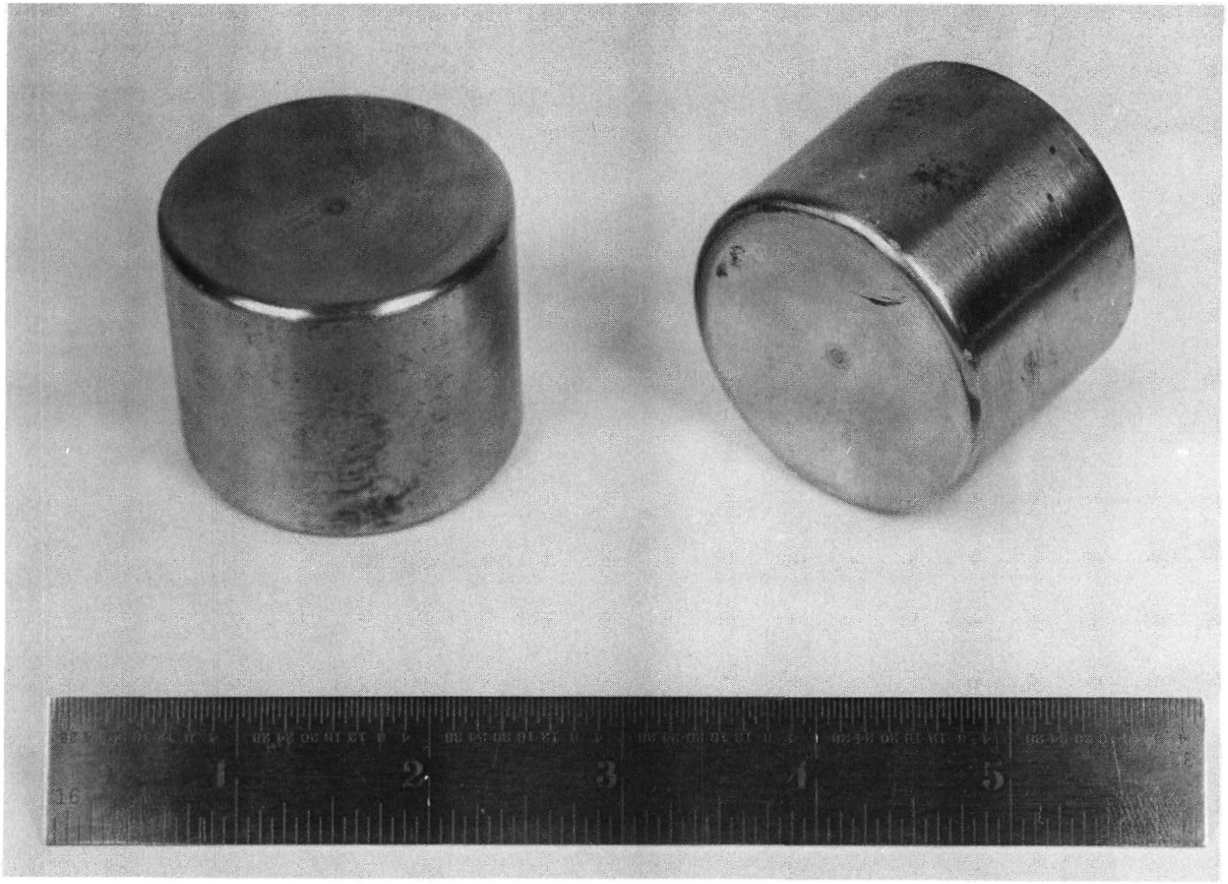


Figure 14 CVM M-50 Preforms Used for Forging of Integral Teeth Gear Blanks

TABLE 3 - As Forged Gear Tooth Dimensions

Deviation From Final Tooth Dimension
(all dimensions in inches)

Tooth Number	Pitch Diameter Left Side	Pitch Diameter Right Side	Outside Diameter	Root Diameter
1	+0.004	+0.004	-0.0075	-0.004
2	+0.003	+0.005	-0.0075	-0.004
3	+0.003	+0.005	-0.0075	-0.004
4	+0.003	+0.005	-0.0075	-0.004
5	+0.003	+0.005	-0.0075	-0.005
6	+0.004	+0.005	-0.0075	-0.005
7	+0.004	+0.005	-0.0075	-0.006
8	+0.004	+0.005	-0.0075	-0.006
9	+0.004	+0.005	-0.0075	-0.006
10	+0.005	+0.005	-0.0075	-0.006
11	+0.005	+0.004	-0.0075	-0.005
12	+0.006	+0.004	-0.0075	-0.005
13	+0.007	+0.003	-0.0075	-0.005
14	+0.007	+0.004	-0.0075	-0.005
15	+0.006	+0.004	-0.0075	-0.005
16	+0.007	+0.005	-0.0075	-0.004
17	+0.007	+0.004	-0.0075	-0.004
18	+0.007	+0.004	-0.0075	-0.006
19	+0.007	+0.005	-0.0075	-0.006
20	+0.008	+0.003	-0.0075	-0.006
21	+0.008	+0.004	-0.0075	-0.005
22	+0.008	+0.004	-0.0075	-0.005
23	+0.008	+0.004	-0.0075	-0.005
24	+0.006	+0.003	-0.0075	-0.004
25	+0.006	+0.005	-0.0075	-0.005
26	+0.006	+0.004	-0.0075	-0.005
27	+0.004	+0.004	-0.0075	-0.005
28	+0.004	+0.004	-0.0075	-0.004

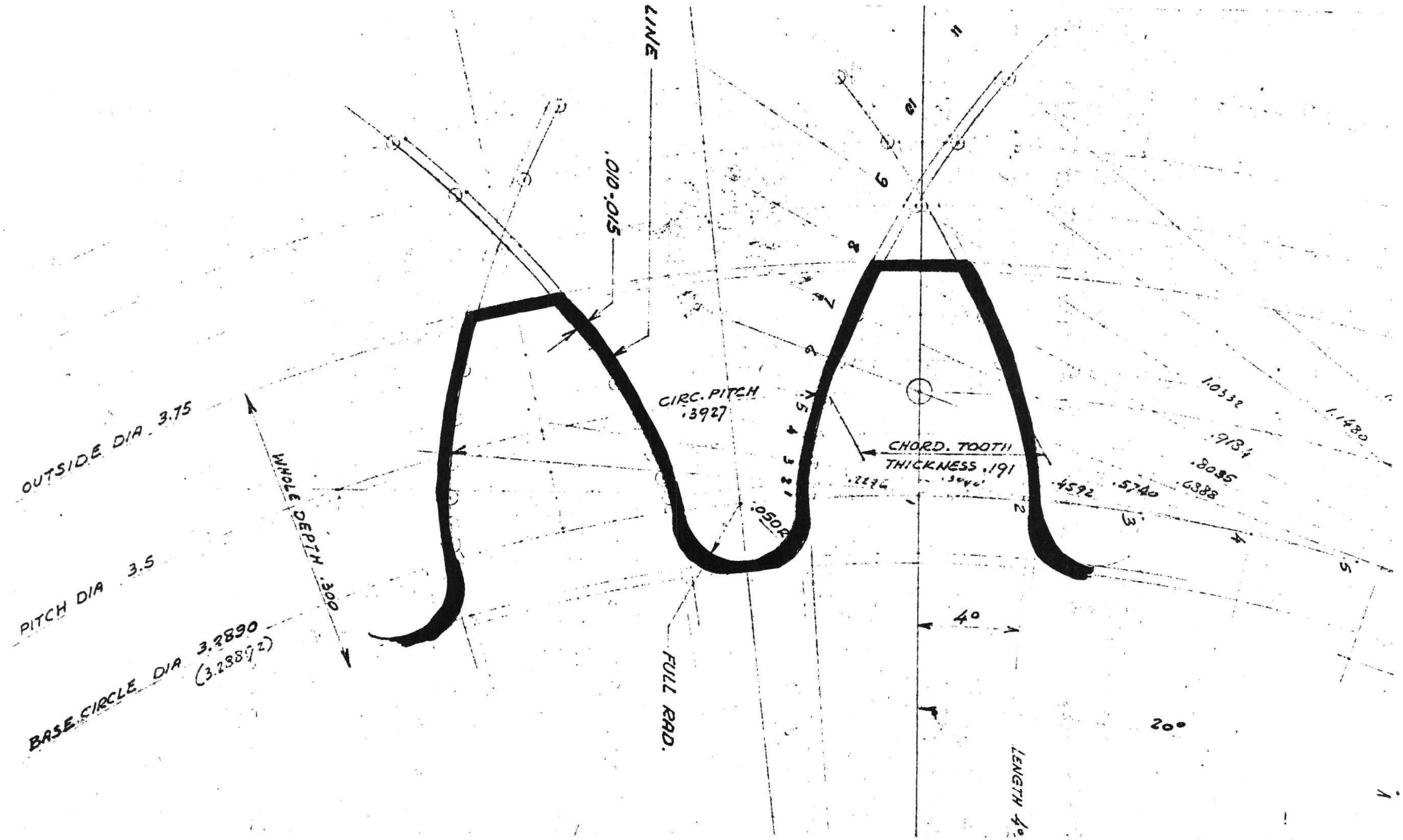


Figure 15 Section of Layout Drawing for Die Used to Forge Gear Blanks. Note Provision for Minimal Material Envelope on Tooth Surfaces

Figure 16 As Forged Gear-Standard Forging Cycle

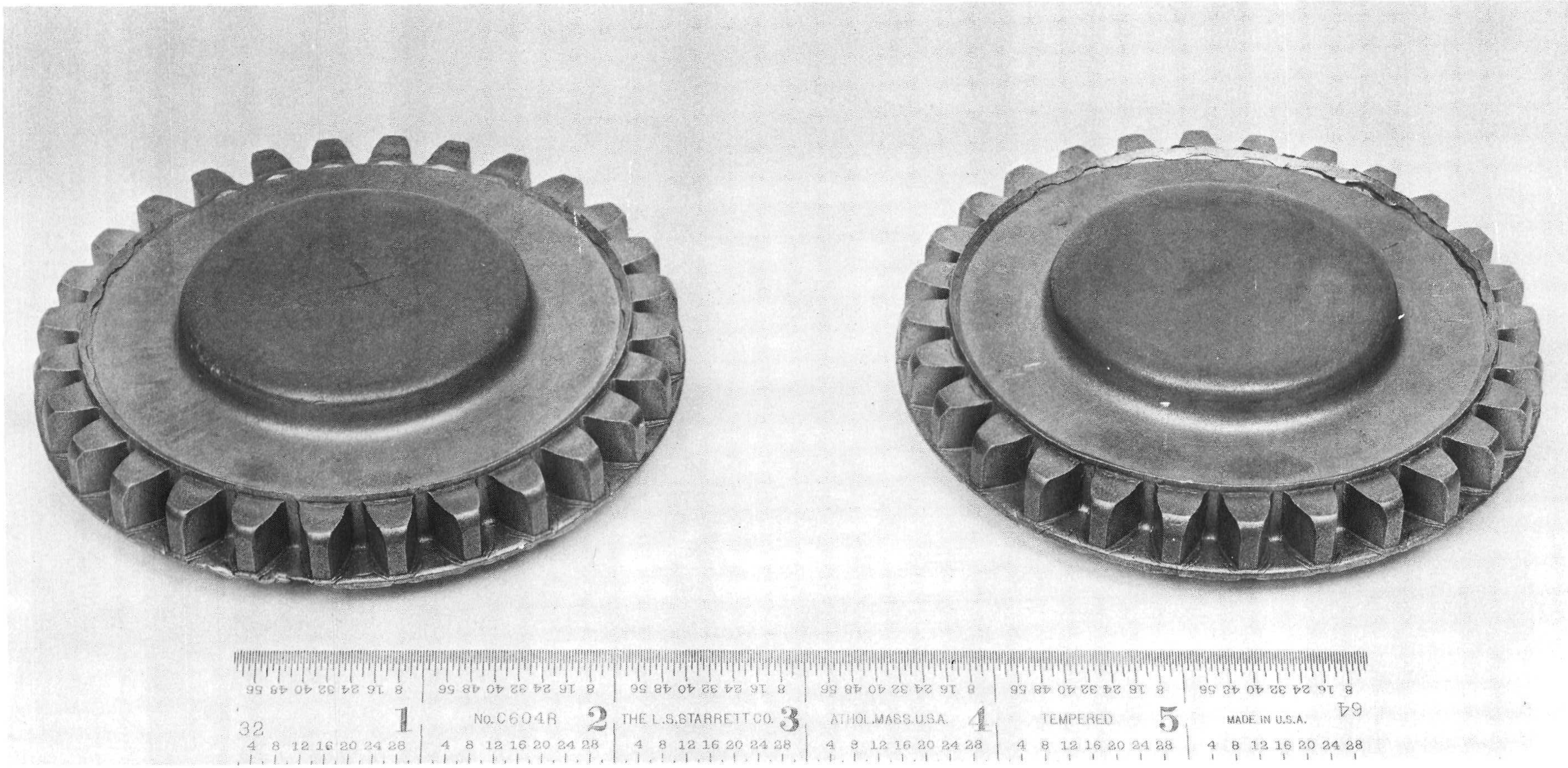


Figure 17 Top View of Standard Forged Gear Blanks

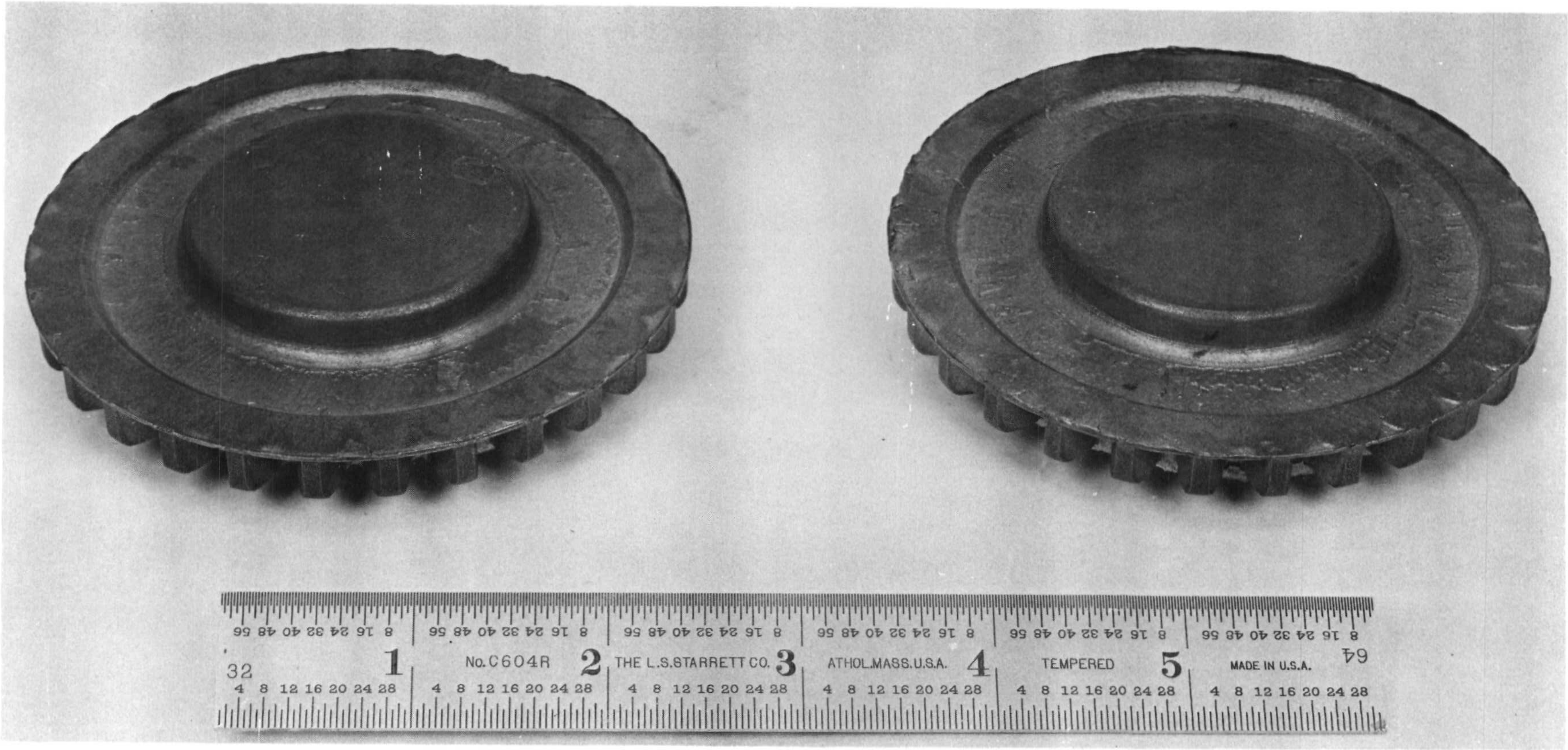


Figure 18 Bottom View of Standard Forged Gear Blanks

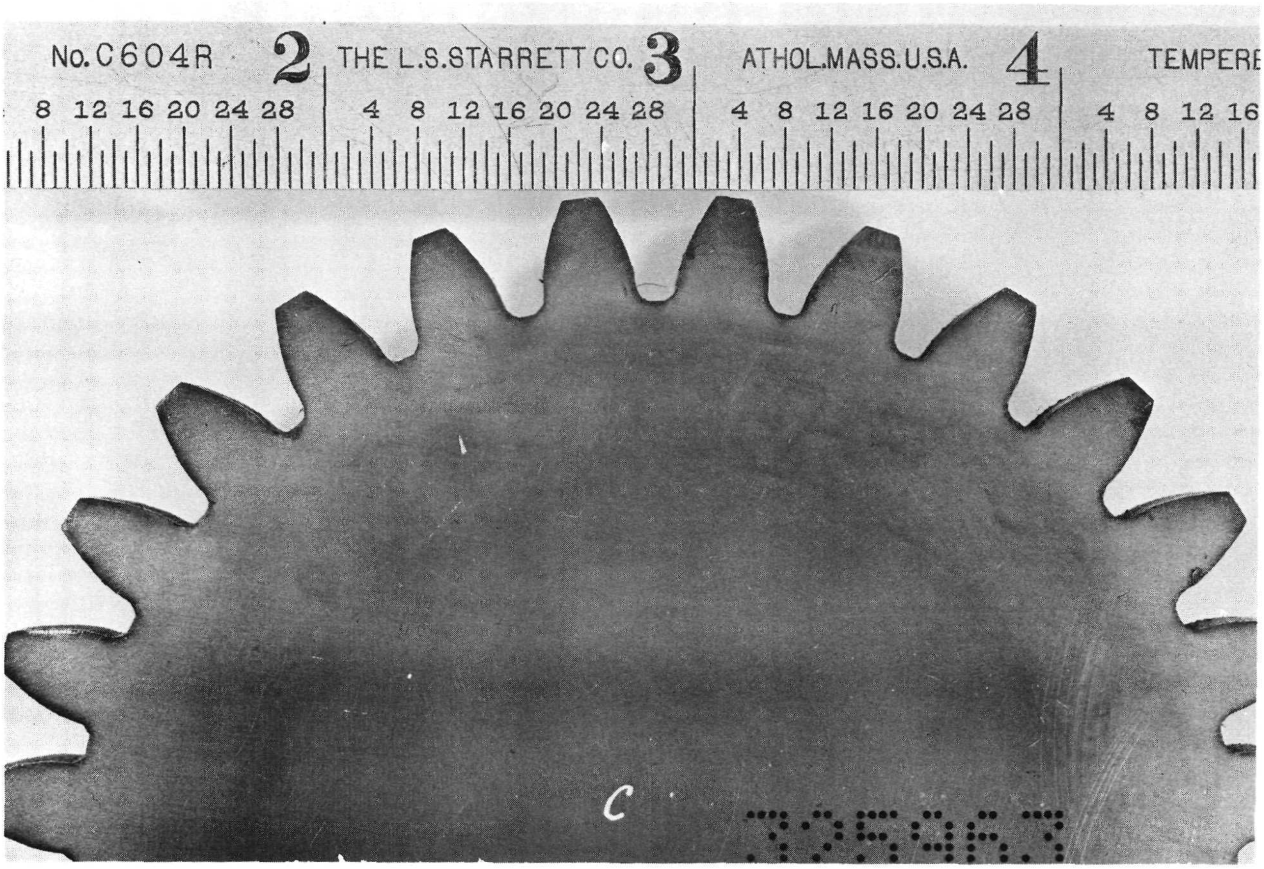


Figure 19 Macro Cross Section Through as Forged Gear Blank

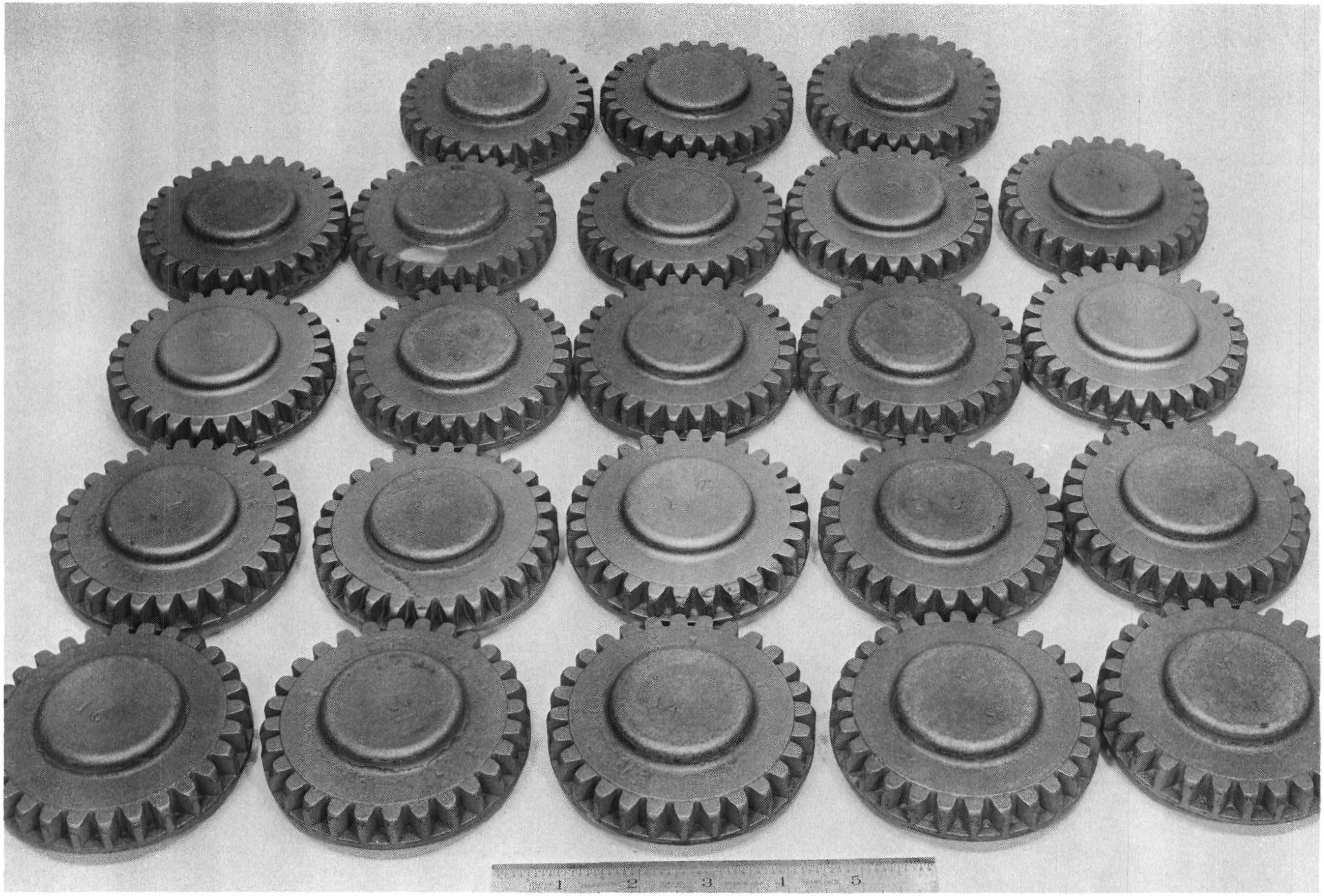


Figure 20 Parts Made During The "Production" Run of Standard Forged Gear Blanks

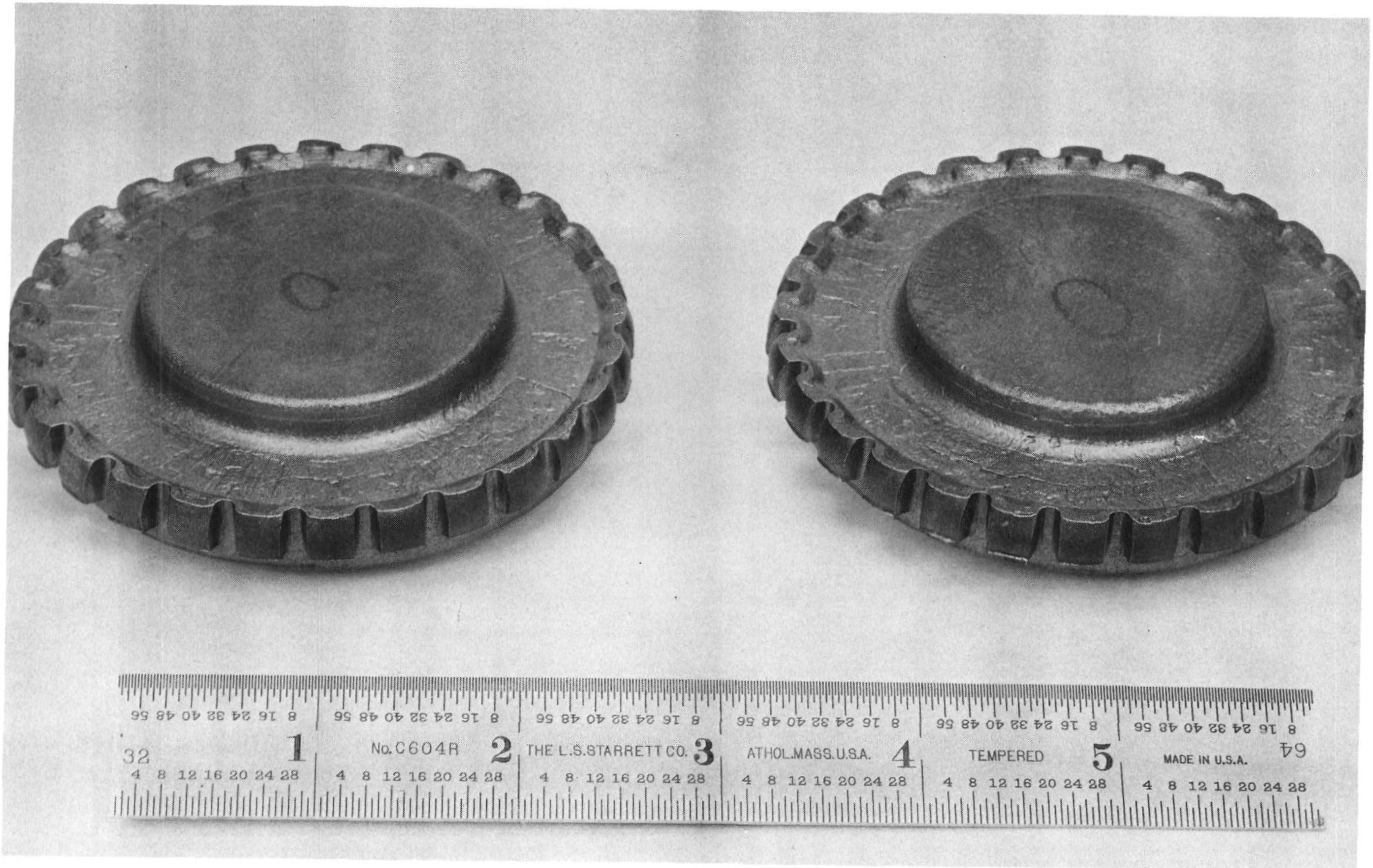


Figure 21 Initial Ausformed Gear Blanks Made on HE-10 CEFF Machine. Note the Minimal Amount of Metal Movement Into the Tooth Configuration

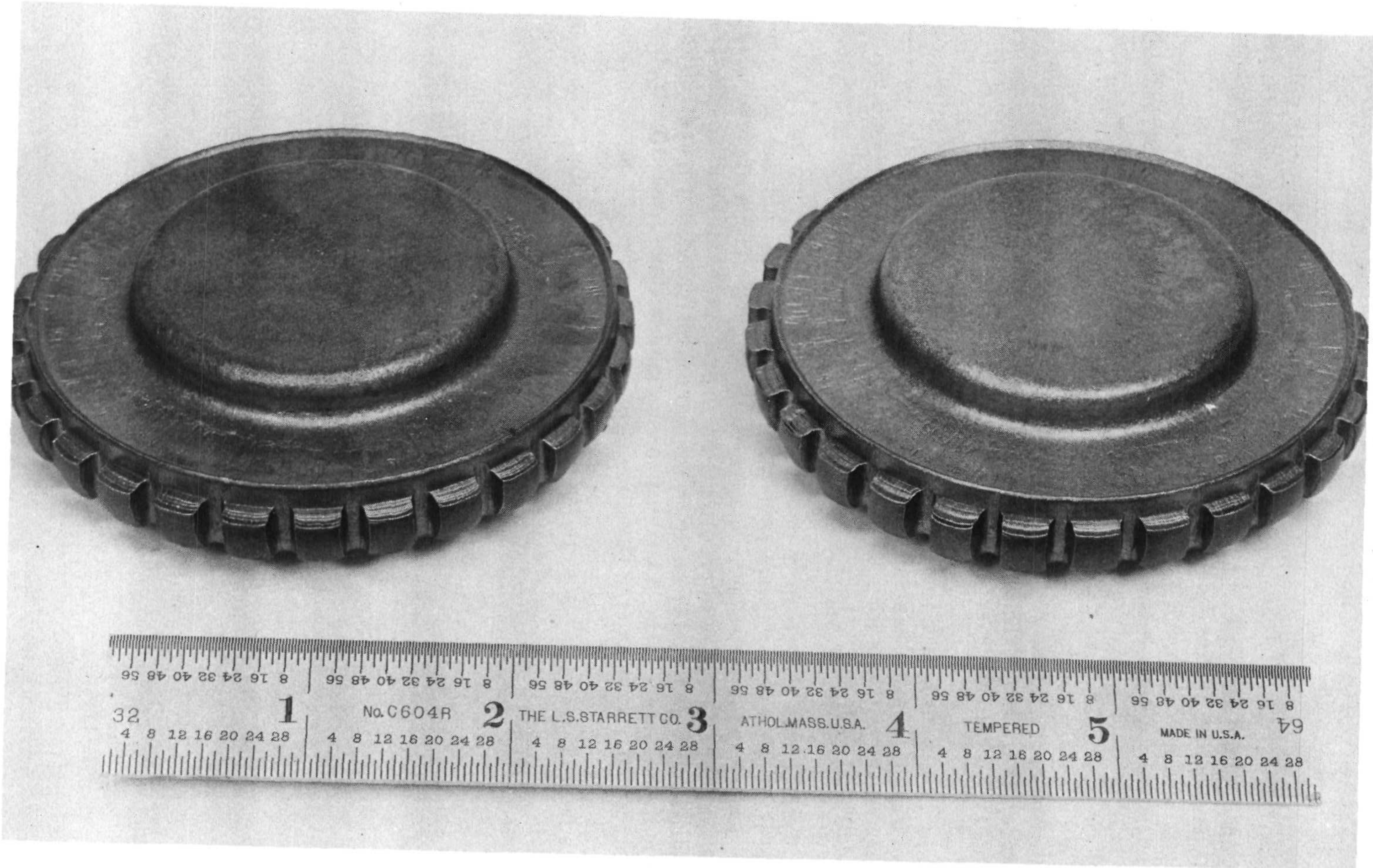


Figure 22 First Ausformed Gear Forgings Made on HE-55 CEFF Machine. Tooth Fill is Better Than That in Figure 21 but Still Unsatisfactory

the ejector to deflect in an elastic manner, since the ejector top face appeared to have maintained its original height after forging. This deflection also resulted in the generation of teeth mislocated from the central hub as indicated in the photograph.

It was reasoned that the significant ejector deflections resulted in the absorption of much of the forging energy and therefore the efficiency of energy transfer to the workpiece was poor. Consequently, tooth fill would be expected to be nonexistent or at best minimal.

An additional tooling and procedural modification remedied this problem to some extent and produced a part shown in Figure 23. It was estimated that the teeth at this point were approximately 60 percent formed and unless relatively major modifications were made, this represented the best part which could be produced.

In reviewing this situation with NASA technical personnel it was concluded that more of the tooth profile would be desirable, and it was consequently decided to attempt to improve the tooth fill condition by a change in the die configuration. This change consisted of adopting a minimal scallop configuration intended primarily to permit a larger radius at the top of the die tooth form (gear tooth radius) which would alleviate the apparent restrictive metal flow. It was also decided to increase the ausforging temperature by 50°F (1525°F) in order to achieve improved flow characteristics.

This was done and the subsequent forging trial produced the parts shown in Figure 24. As can be seen, full tooth configuration has essentially been achieved, although the lack-of-fill condition of the upper part of the teeth still made this a marginal part in terms of the final machined tooth width of 1/4 inch.

One final modification was therefore in order, which consisted of increasing the height of the tooth insert tooling coupled with an equivalent increase in the volume of the preform. These measures were designed to increase the tooth height and thus provide adequate material for final machining. These corrective steps were successful and resulted in the production of dimensionally acceptable parts. These are illustrated in Figures 25 through 29. The only problem encountered was a heavier than expected flash area (illustrated in Figure 26) which required more time during final machining.

The die inserts held up remarkably well, as shown in Figure 30. While there is some evidence of scouring and upsetting, no serious damage or tooth breakage was encountered.

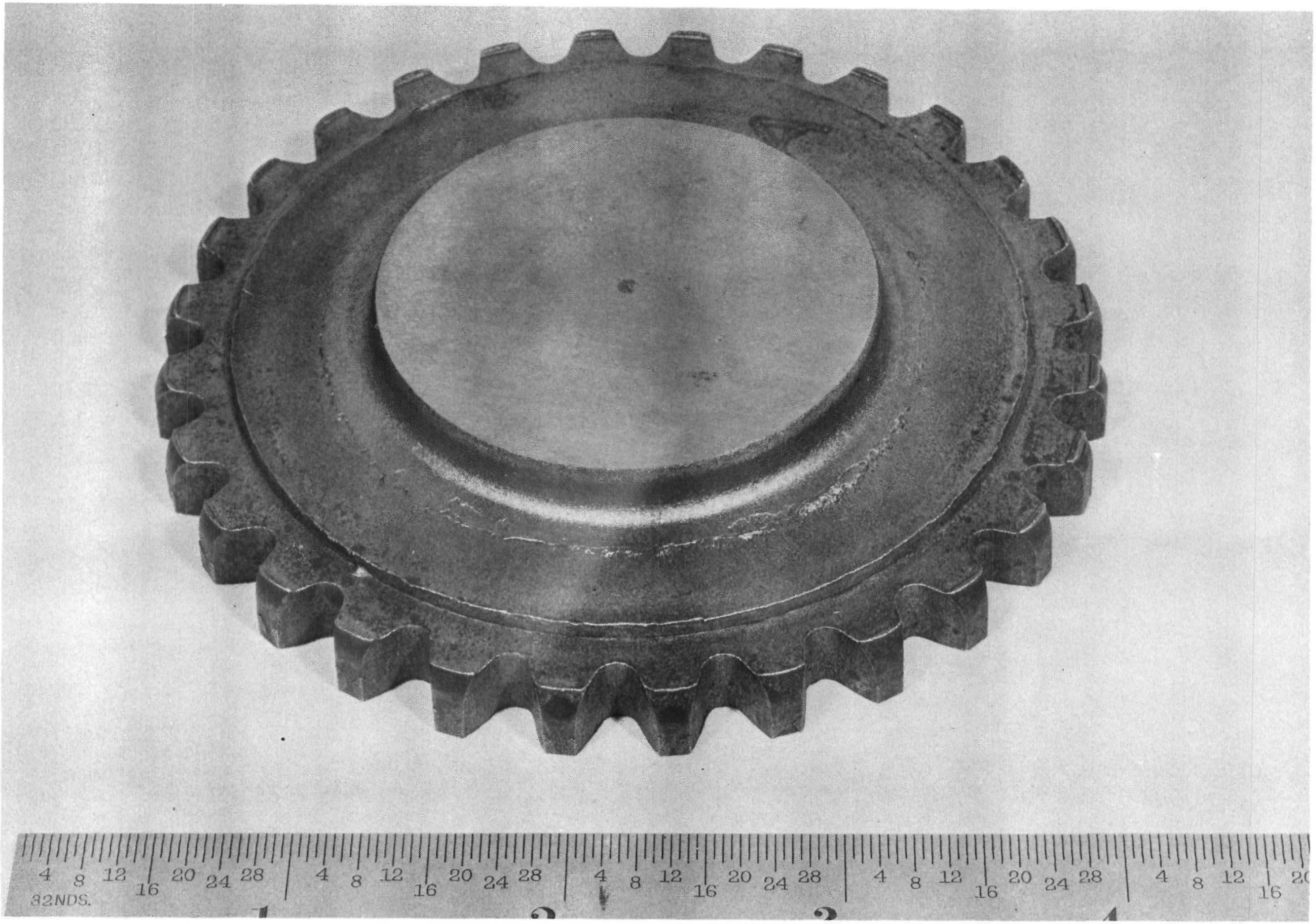


Figure 23 Ausformed Gear After Initial Tooling & Process Modification. Tooth Fill is Approximately 60 Per Cent

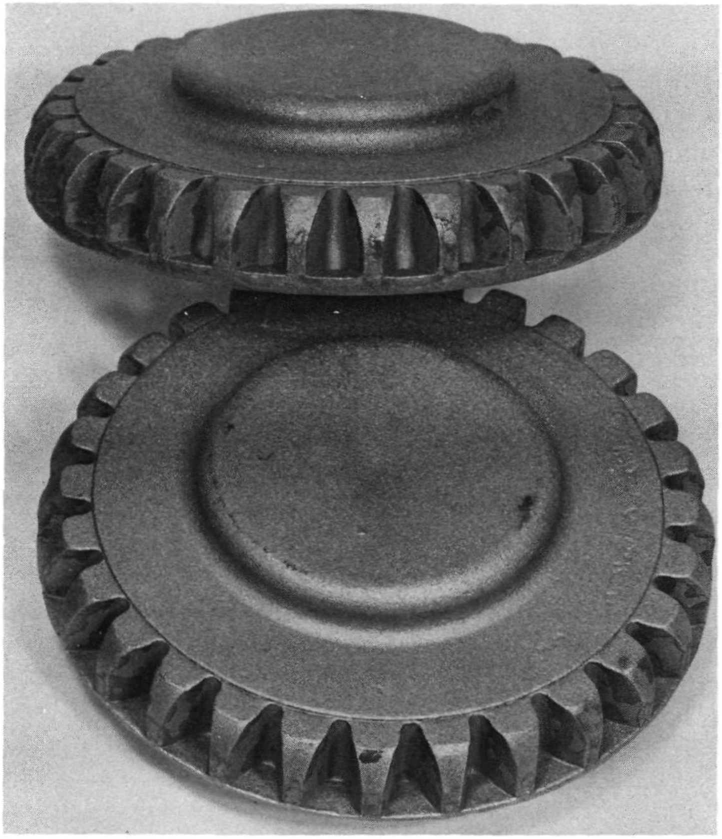


Figure 24 Ausformed Gear Forgings After Additional Tooling and Die Modifications, 100 Per Cent Tooth Configuration Has Been Established Although Lack of Fill at Bottom (Upper Surfaces in Photograph) Has Created Condition of Minimal Tooth Width

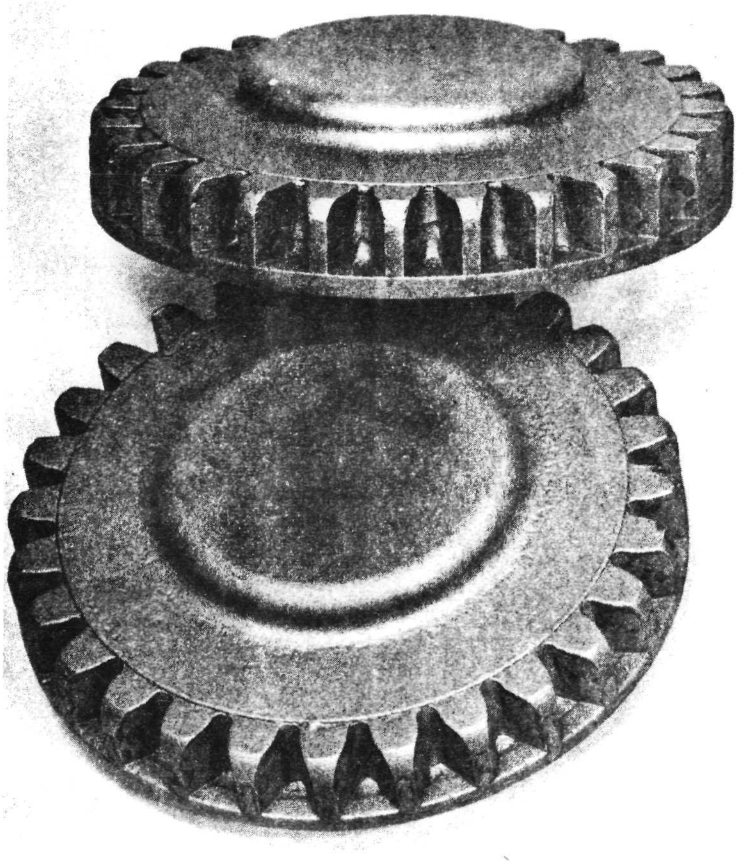


Figure 25 Ausformed Gear After Increasing Height of Tooling

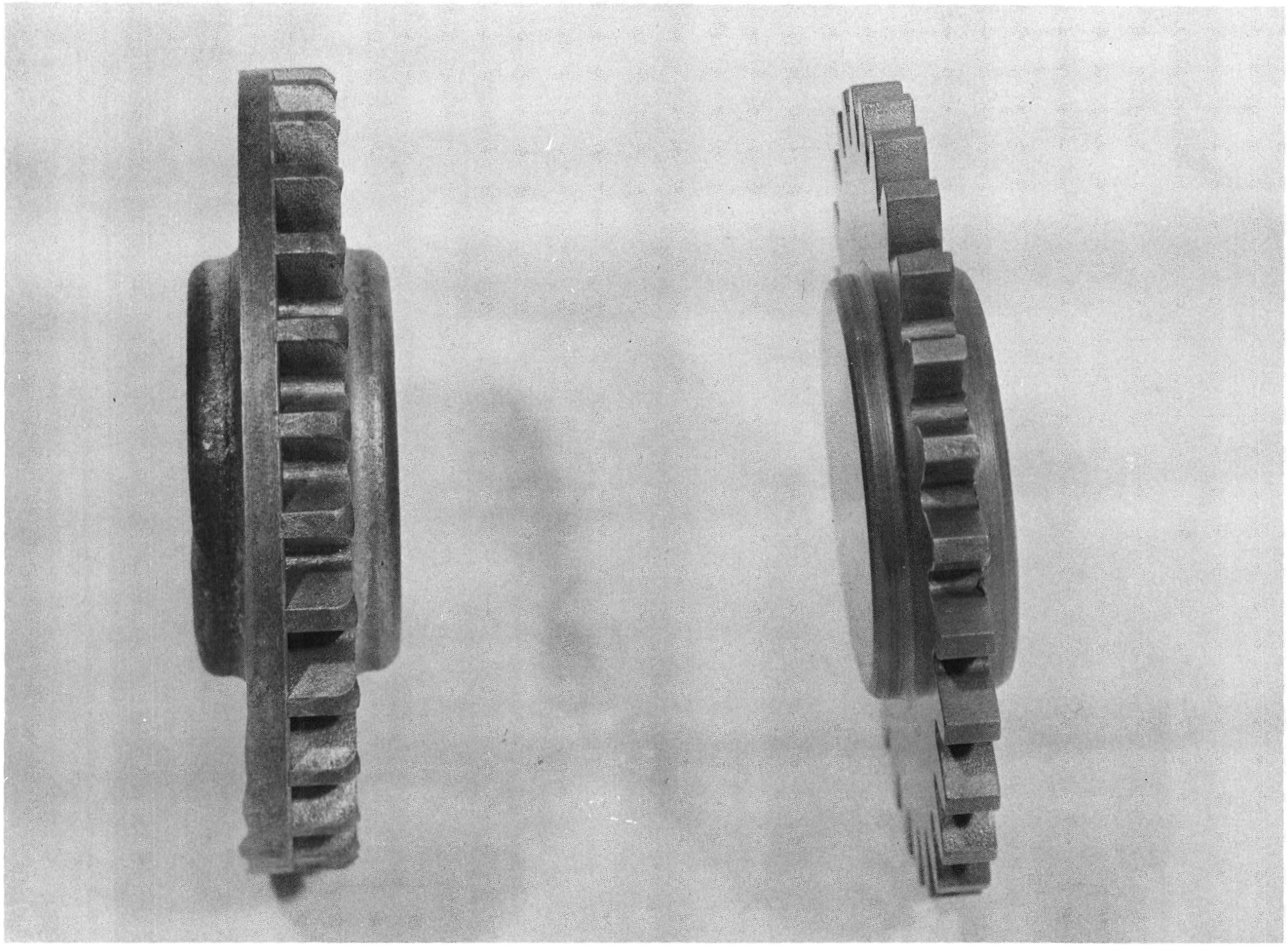


Figure 26 As Ausforged Gear Blank (Left) and Semi-Machined Gear (Right)

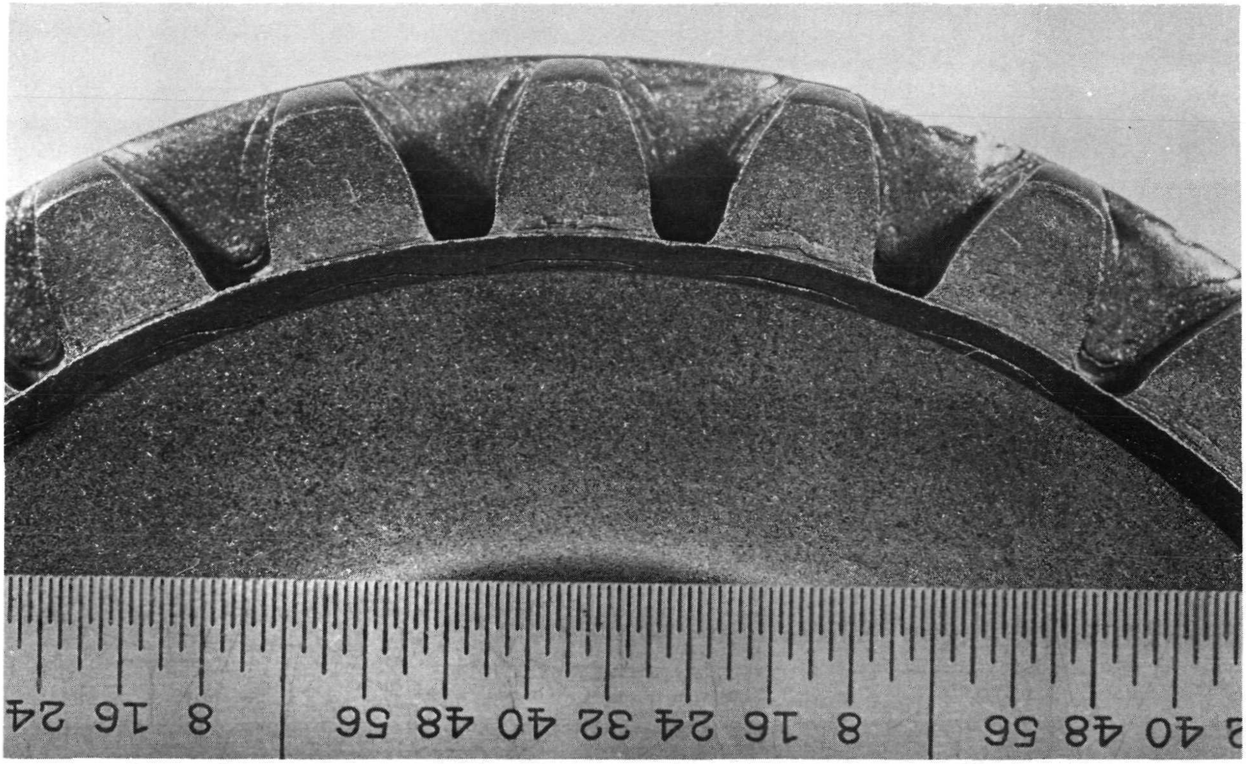


Figure 27   Macro of Ausformed Gear Teeth. Note Minimal Scallop Configuration in Bottom Radius

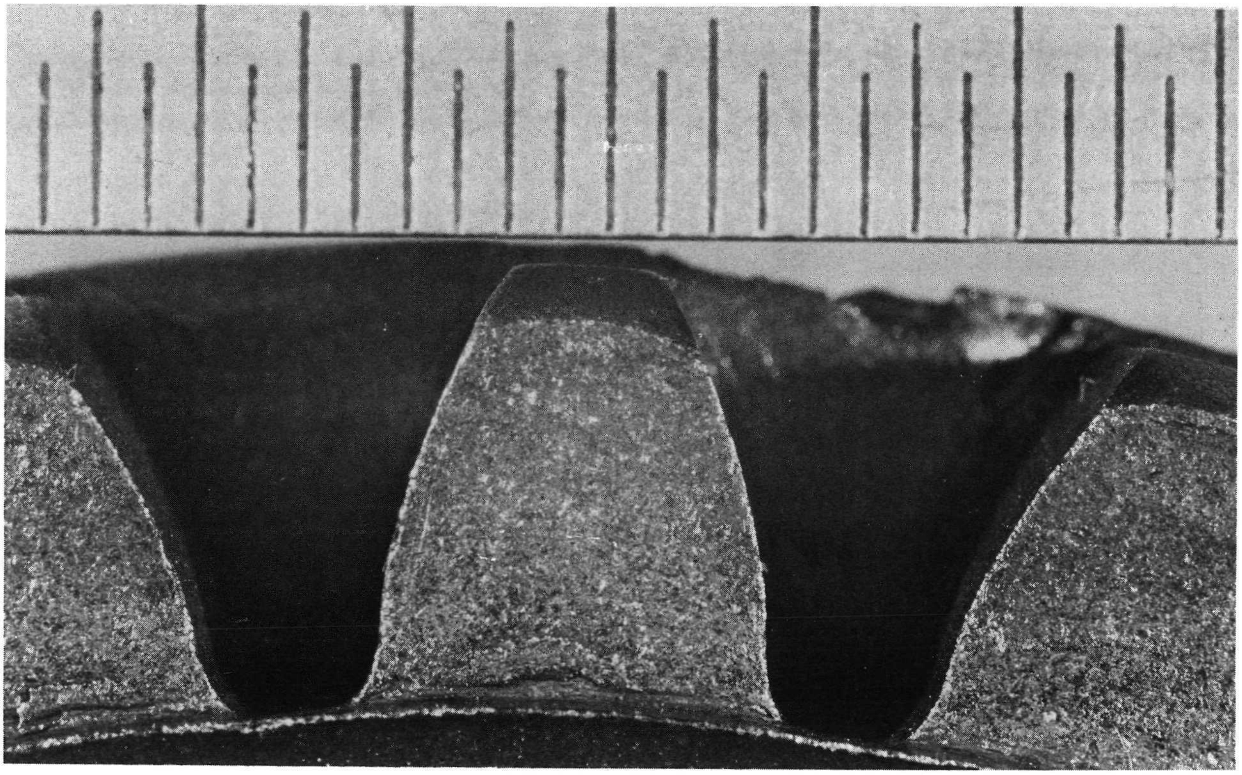


Figure 28 Close-Up of Ausformed Gear Tooth

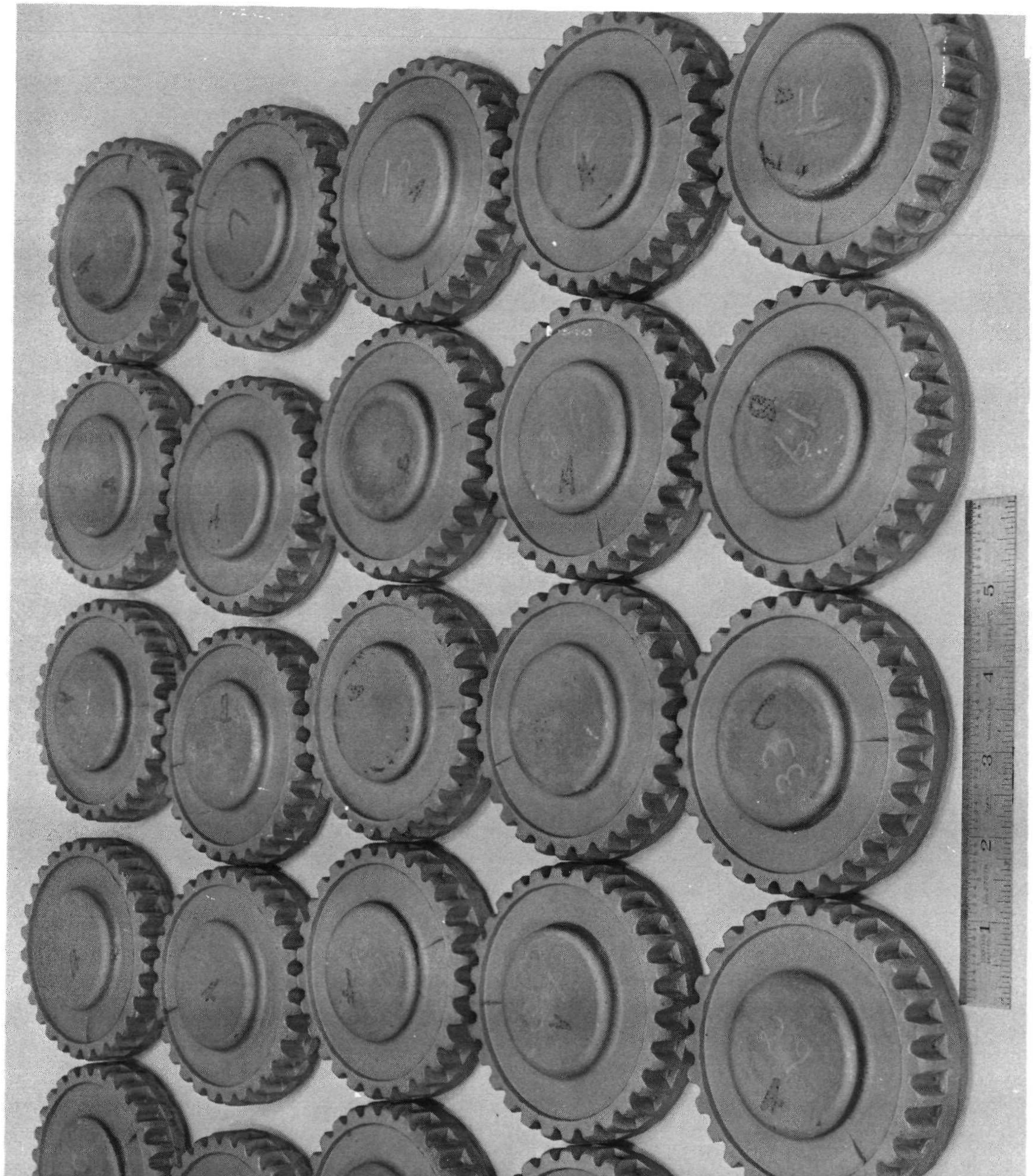


Figure 29 Parts Made During "Production" Run of Ausformed Gears

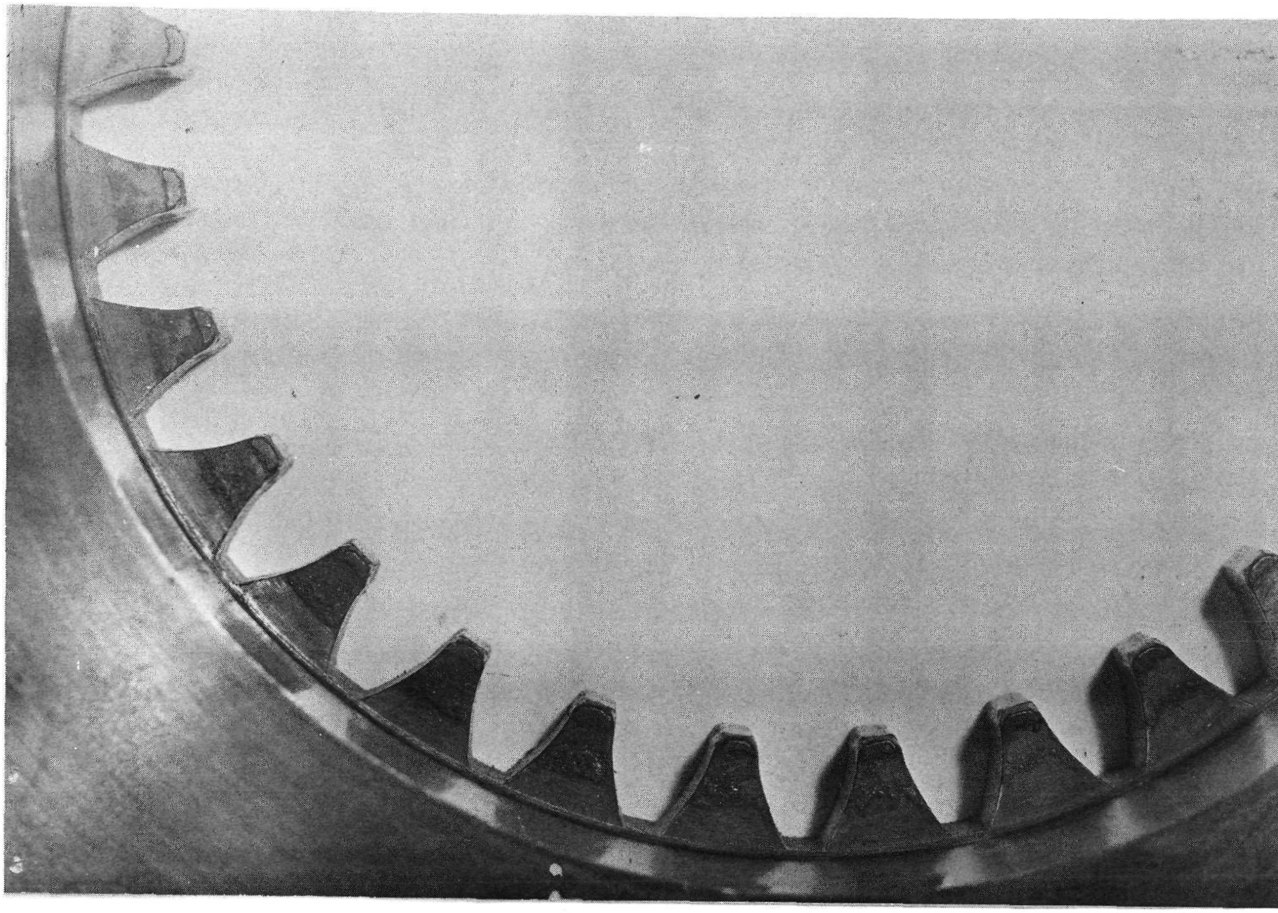


Figure 30 Section of Die Insert After Production Ausforming Run

9.0 METALLURGICAL EXAMINATION

The inherent metallurgical characteristics contributing to the beneficial effects of ausforming on rolling element and bending fatigue life have been discussed at length in the technical literature. In respect to gear materials these beneficial effects are directly relevant and should provide a favorable array of properties. There is, however, one additional aspect in gear technology which is critical to the successful operation of highly loaded gear trains. This is the bending moment at the base of the tooth which can precipitate tooth breakage long before the more normal scuffing or fatigue spalling failures are encountered. The resistance to bending fatigue in gear materials is of particular concern when through hardened materials (such as M50) are used. In the current program, a major objective therefore was to attenuate this problem by generating a macro grain-flow pattern which would be conducive to improved tooth radius fatigue strength. The schematic sketch in Figure 31 illustrates this concept. In the design of the forgings considerable attention was therefore directed toward the generation of a good grain flow pattern in the gear tooth radius, as well as along the contact areas. This consideration was also a factor in the attempt to achieve a minimum as forged material envelope, as it was felt that any subsequent machining would tend to reduce the beneficial grain flow depth.

As can be seen in Figures 32 and 33 the actual grain flow pattern which was achieved was generally as had been planned. The additional photomicrographs shown in Figures 34 and 35 illustrate the typical microstructure expected with ausformed M50.

Hardness, always a good indicator of the effectiveness of the ausforming procedure was Rc62-64 as forged and did not vary as a result of the temper or stress relief cycles. Typical hardness surveys on as forged and final machined ausformed gear teeth are shown in Figures 36 and 37.

The standard forged gears exhibited the same grain flow pattern as their ausformed counterparts. The standard forged parts were semimachined, (within .006 inches of final dimension) heat treated to achieve full hardness and then finish machined. The hardening cycle was as follows:

Preheat: 1500° ± 5°F/30 minutes (salt)

Austenitize: 2035°F ± 5°F/5 minutes at temperature (10 minutes total time, salt bath)

Quench into 1065°F ± 10°F Salt - hold for ten minutes

Air cool to room temperature

Temper 1025°F ± 5°F/2 hours

Air cool

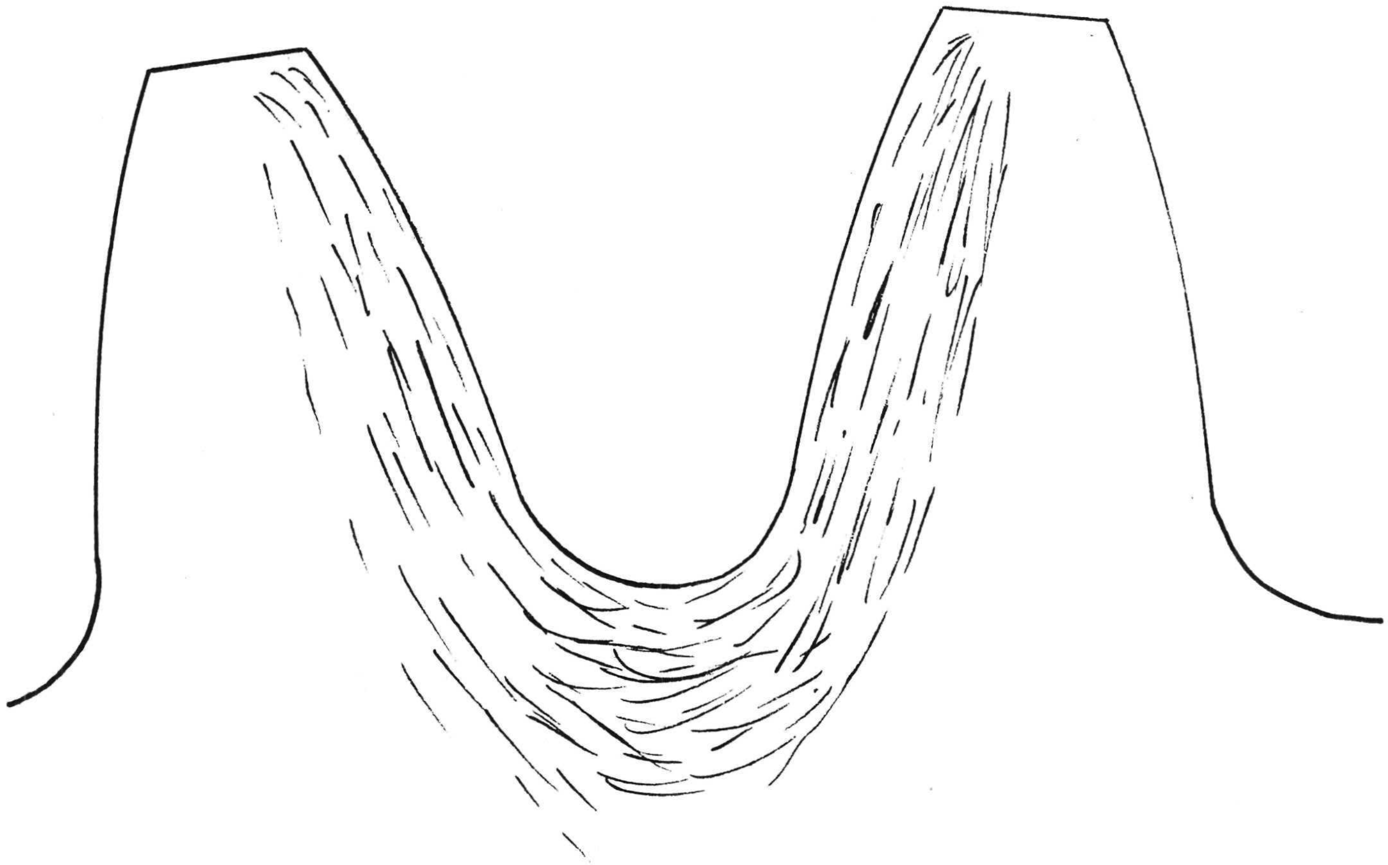


Figure 31   Schematic of Preferred Macro Grain-Flow Pattern in Gear Tooth

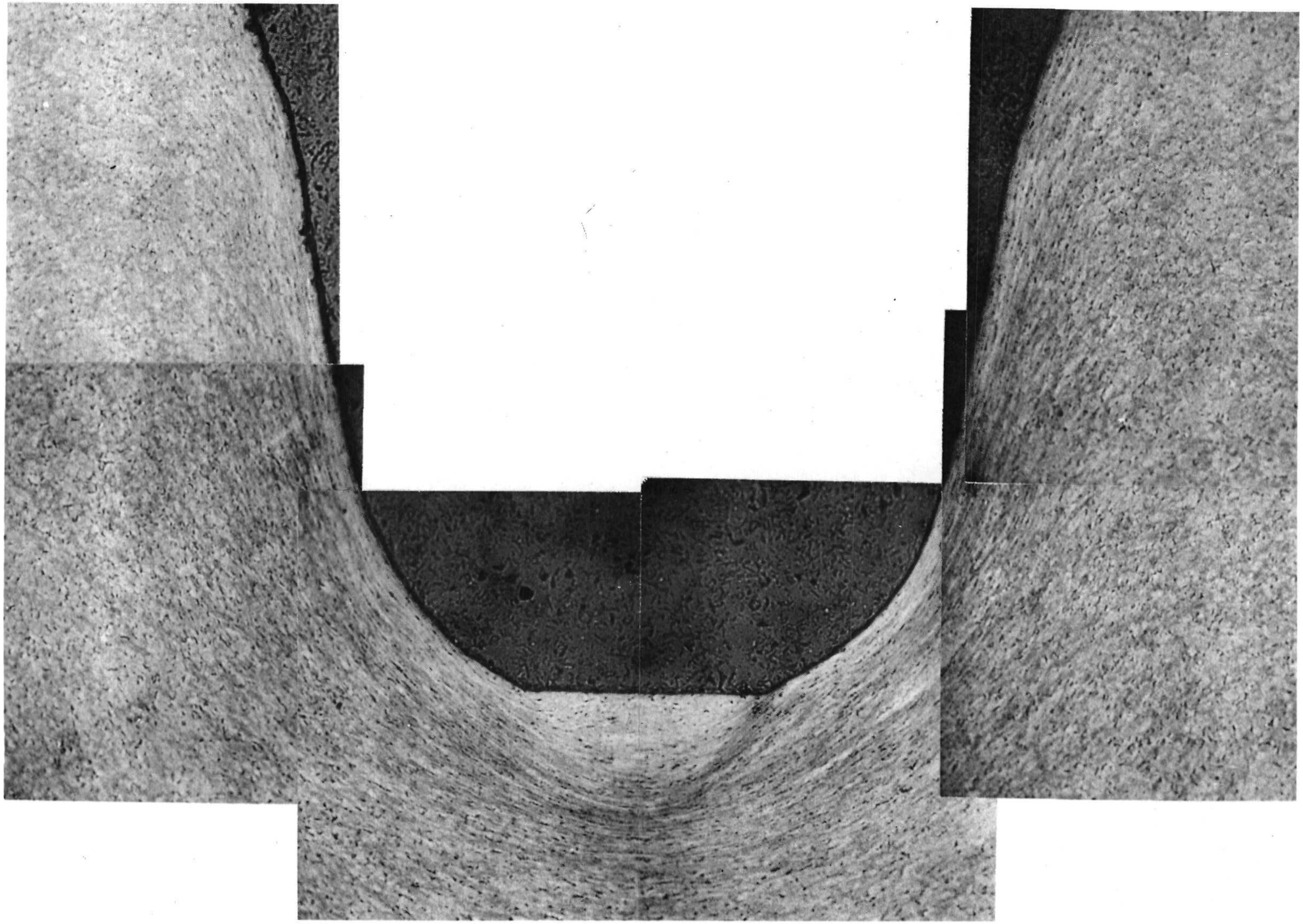


Figure 32 Macro Grain-Flow Pattern in Standard Forged Gear. Original Mag: 50X, Etchant: 3% Nital

Figure 33 Macro Grain-Flow Pattern in Ausforged Gear. Original Mag: 25X, Etchant: 3% Nital

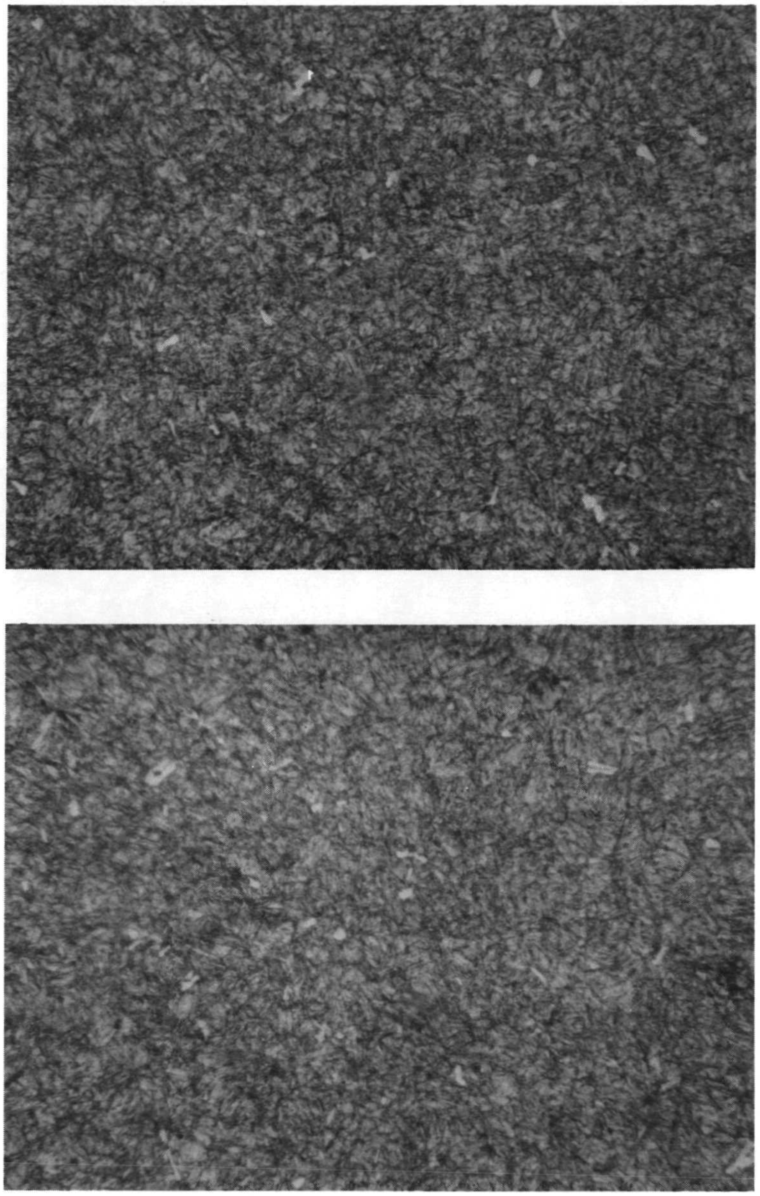


Figure 34 Typical Microstructure in Tooth of Ausformed Gear.
Mag: 500X, Etchant: 3% Nital

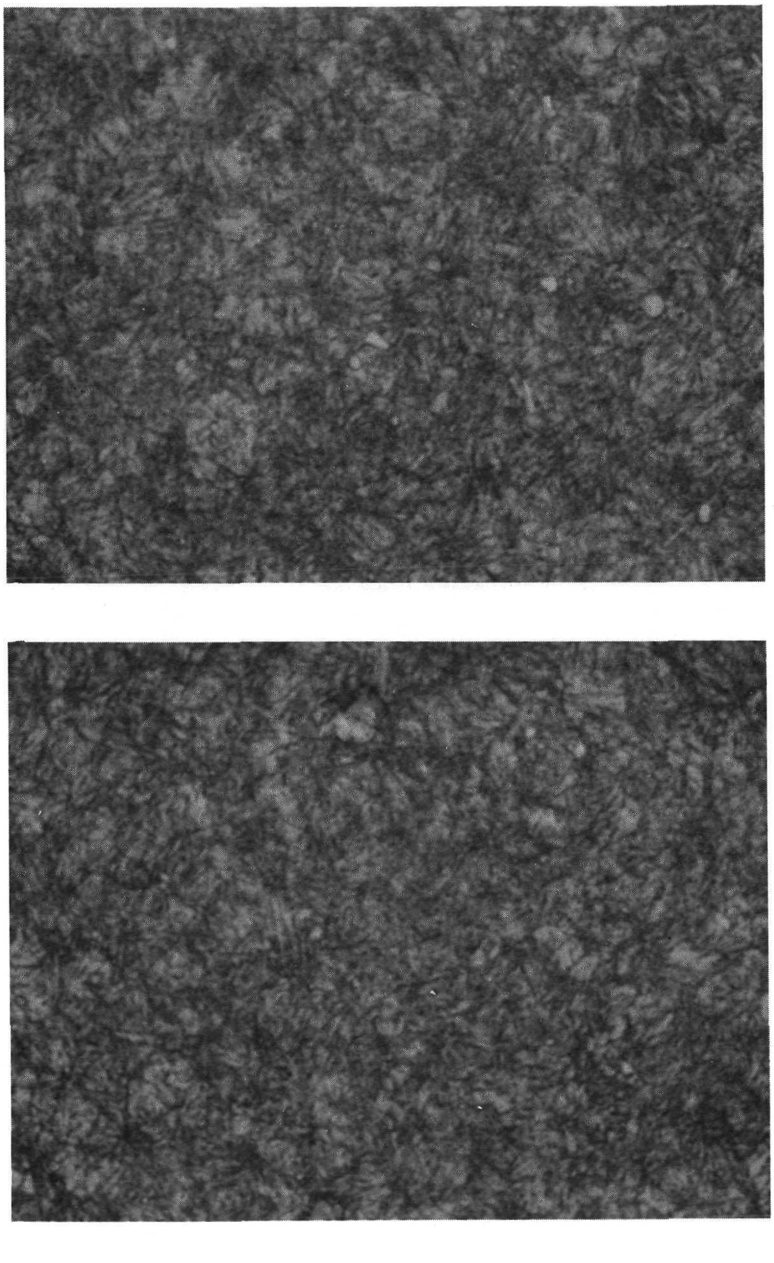
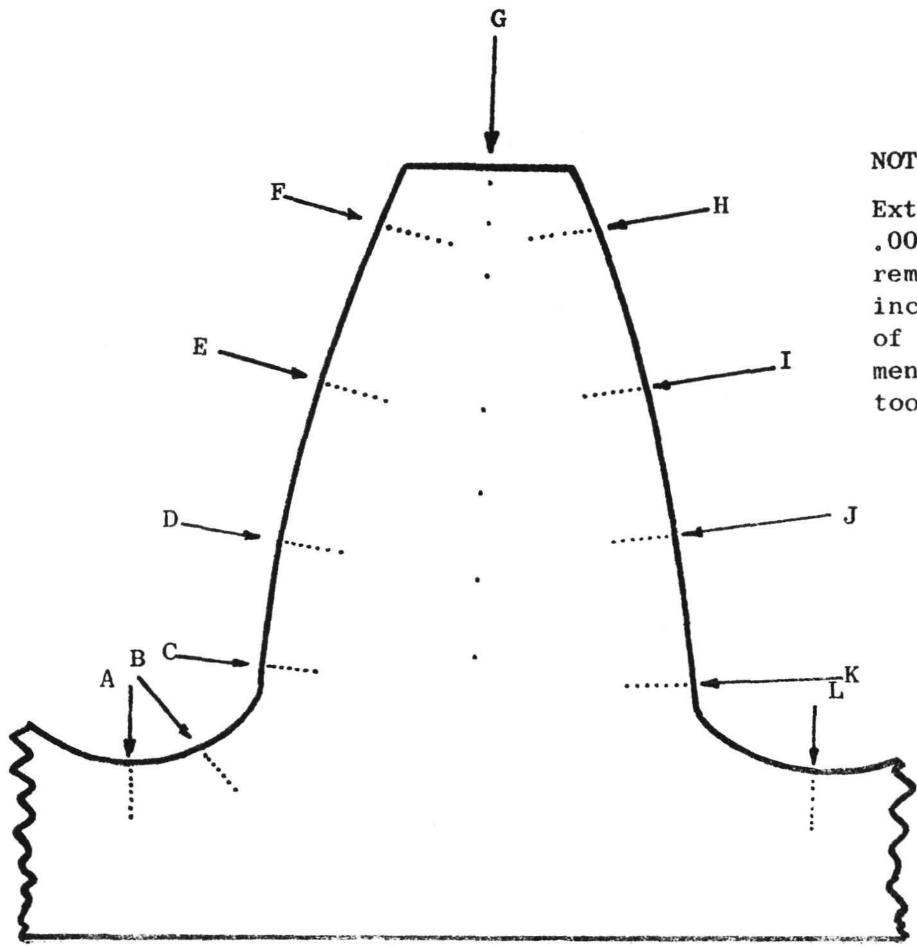


Figure 35 Typical Microstructure in Tooth of Ausformed Gear.
Mag: 1000X, Etchant: 3% Nital



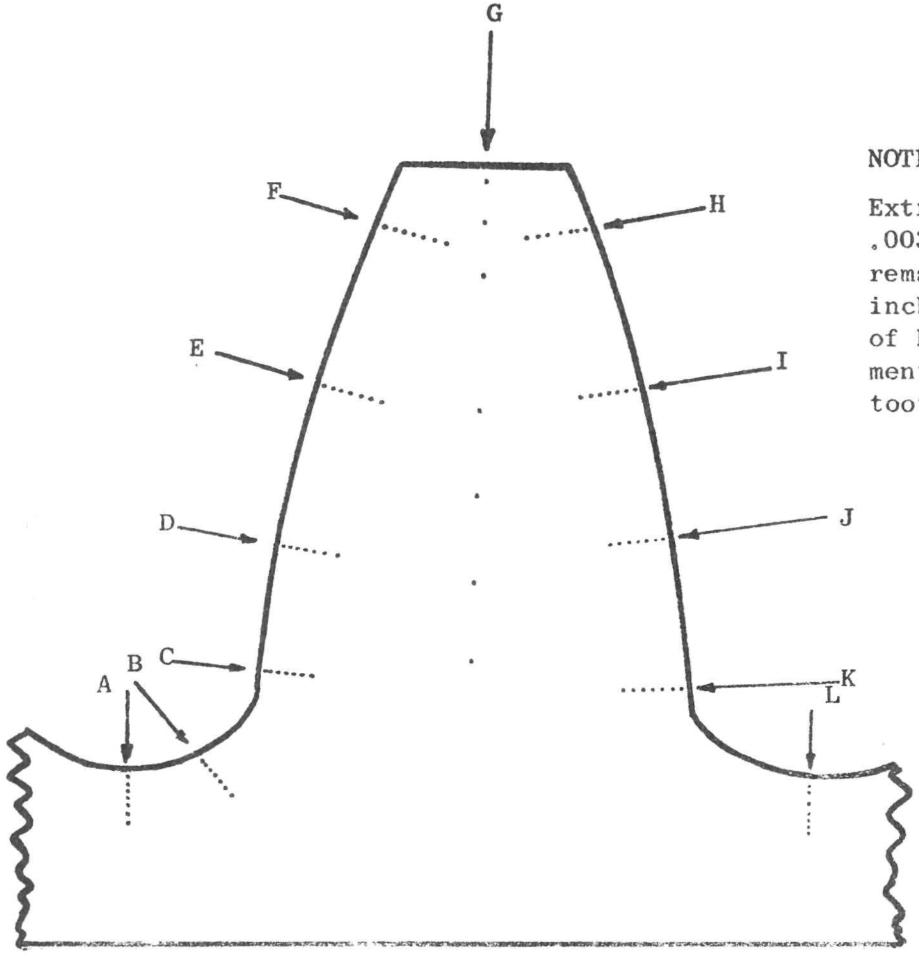
NOTE:

Extreme outside measurement is ~ .003 - .004 inches from surface, remaining measurements are at .010 inch increments, with exception of Row G. In latter, survey measurements are spaced to cover total tooth height.

Rockwell "C" Hardness - converted from 500 g. DPH Microhardness Measurement

	Row A	Row B	Row C	Row D	Row E	Row F	Row G	Row H	Row I	Row J	Row K	Row L
1	62-64	62-64	63	63	63-64	63	62	63-64	63	63-64	63	63
2	62-64	62-64	63	63	63-64	63	62	63-64	64	63	63	63
3	62-64	63	63	63	63-64	63-64	62	63	63	63	63	63
4	63	63	63	63	63	63	61.5	63	63-64	63-64	62-64	63-64
5	63	63	62-63	63	63	63	61.5	63	63	63	63	63
6	62	63-64	62-63	63	62	63	61.5	63	63	63	63	63
7	62	63	62-63	63	63	62	61	63	63	63	63	63-64

Figure 36 Hardness Survey On As-Forged Ausformed Gear Tooth



NOTE:

Extreme outside measurement is ~ .003 - .004 inches from surface, remaining measurements are at .010 inch increments, with exception of Row G. In latter, survey measurements are spaced to cover total tooth height.

Rockwell "C" Hardness - converted from 500 g. DPH Microhardness Measurement

	Row A	Row B	Row C	Row D	Row E	Row F	Row G	Row H	Row I	Row J	Row K	Row L
1	63-64	63-64	63	63-64	63-64	63-64	62-63	63-64	63-64	63-64	63	63-64
2	63	63	63	63-64	63-64	63	62-63	63	63	63-64	63	63
3	63	63	62-63	63-64	63	63-64	62	63	63	63	63-64	63
4	63	63	63	63	63	63	62	63	63	63	63	62-63
5	63	63	63	63	63	63	61.5	63	63	63	63	63
6	62-63	63	63	63	62-63	63	62	63	63	63	63	63
7	62-63	62-63	63	63	63	63	61.5	63	63	63	63	62-63

Figure 37 Hardness Survey On Semi-Machined Ausformed Gear Tooth

Subzero cool - 100°F/2 hours

Warm to room temperature

Temper 1025°F ± 5°F/2 hours

Hardness measurements taken on all gears after the heat treatment showed a range of Rc63 - Rc64. Metallographic examination of one of the gears showed no evidence of decarburization. X-ray diffraction measurements to determine the amount of retained austenite were also made on the extra gear. These measurements showed the percentage of retained austenite to be less than one percent.

A typical microstructure of the fully heat treated M50 gear is shown in Figure 38. A hardness survey (Figure 39) of the gear teeth showed extremely good consistency in hardness.

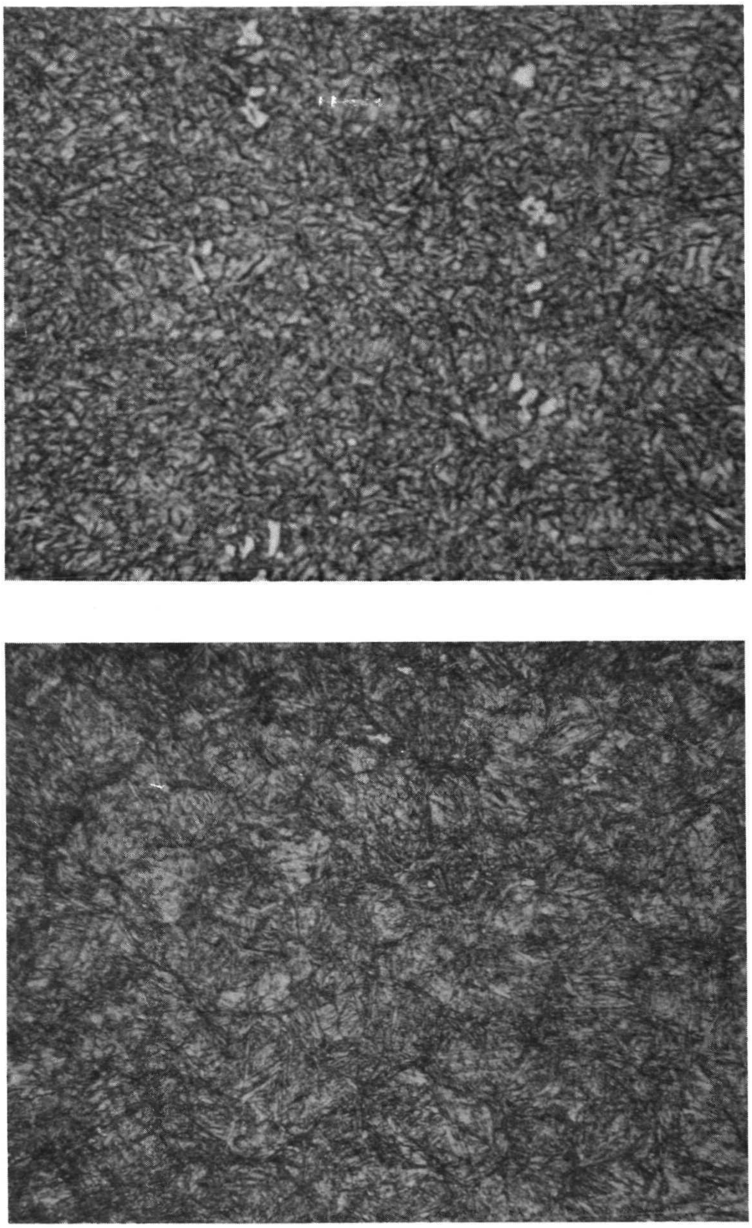
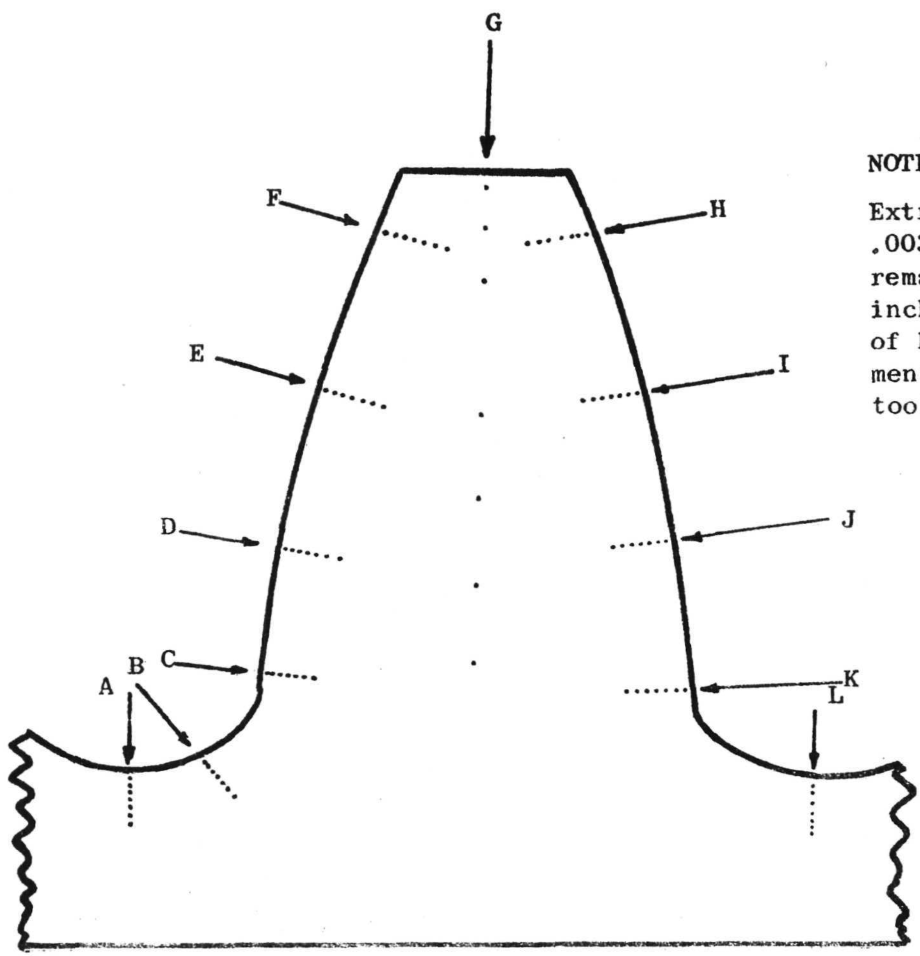


Figure 38 Typical Microstructure in Tooth of Standard Forged Gear.
Mag: Top - 500X, Bottom - 1000X; Etchant: 3% Nital



NOTE:

Extreme outside measurement is ~ .003 - .004 inches from surface, remaining measurements are at .010 inch increments, with exception of Row G. In latter, survey measurements are spaced to cover total tooth height.

Rockwell "C" Hardness - converted from 500 g. DPH Microhardness Measurement

	Row A	Row B	Row C	Row D	Row E	Row F	Row G	Row H	Row I	Row J	Row K	Row L
1	63	63	63	63-64	63	63	63-64	63	63	63	63	63-64
2	63	63	63	63	63	63	63	63	63	63	63	63-64
3	63	63	63	63	63	63	63	63	63	63	63	63
4	63	63	63	63	63	62	63-64	63	63	63	63	63
5	63	63	63	63	63	63	63	63	63	63	63	63
6	63	63	63	63	63	63	63	63	63	63	63	63
7	63	63	63	63	63	63	63	63	63	63	62	63

Figure 39 Hardness Survey On Standard Forged and Fully Heat-Treated Gear Tooth

10.0 GEAR MACHINING - INSPECTION

The standard forged and ausformed gear blanks were finish machined to NASA Drawing #CD850863 by the Indiana Gear Works Division, Buehler Corp., Indianapolis, Indiana.

The standard forged gears, which were in the soft, annealed condition, were semi-finished machined, i.e., having an excess material envelope of .006 inches, and then returned to General Electric for heat treatment. The heat treat cycle has been detailed in an earlier section of this report. The parts were then finish machined by IGW.

The ausformed gears, being in the fully hardened condition required a different manufacturing cycle. Initially, the excess material was removed by electrochemical machining. Similarily, the center was trepanned by ECM, following which the remainder of the tooth profile as well as the other dimensions were obtained by stress free grinding. The standard forged gears after heat treatment are shown in Figures 40 and 41. A fully machined ausformed gear is shown in Figure 42. In Figure 43 the starting preform as well as the finish machined gear are shown and finally in Figure 44 the four major steps in the production of the ausformed gears are illustrated.

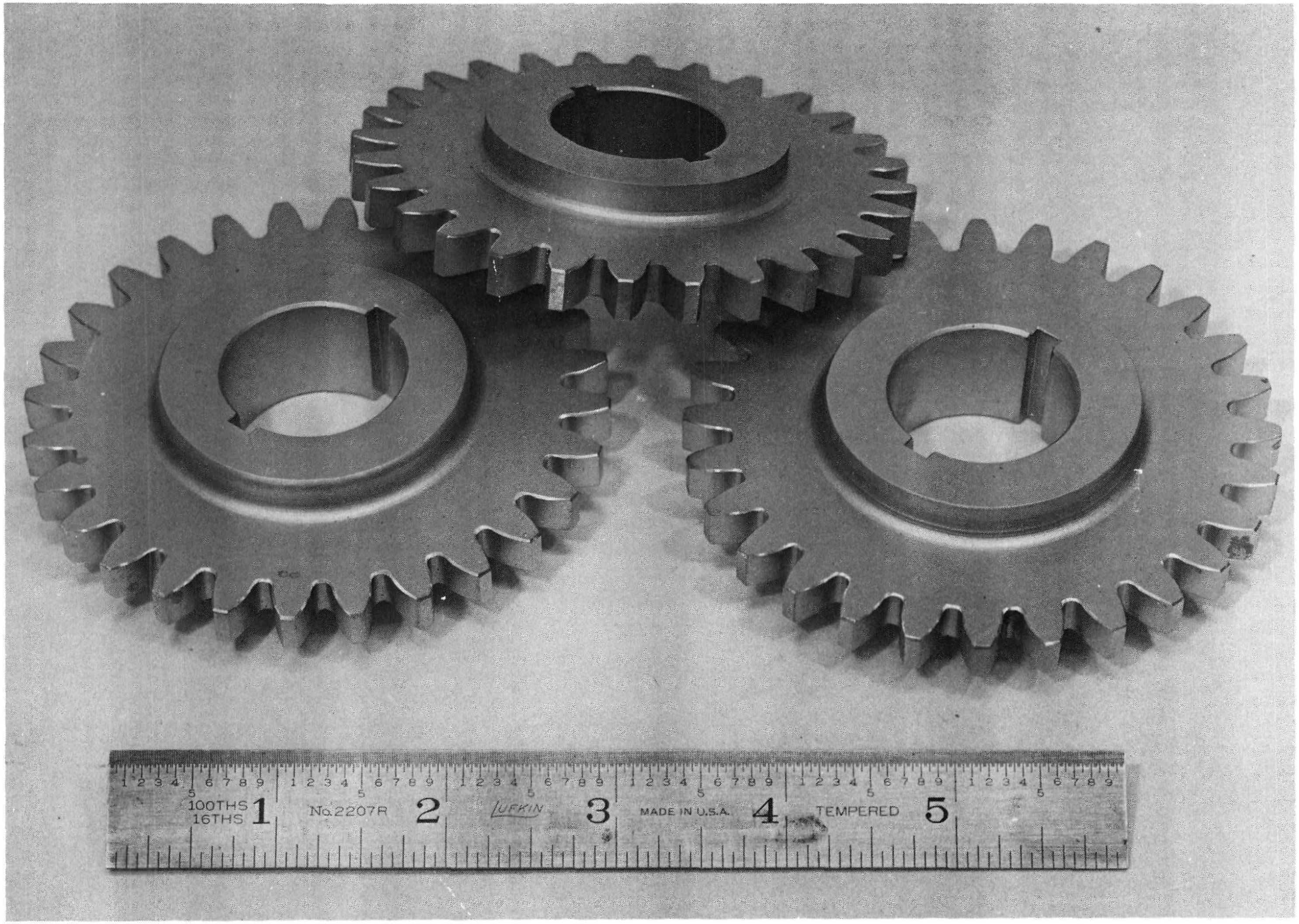


Figure 40 Semi-Finish Machined Standard Forged Gears

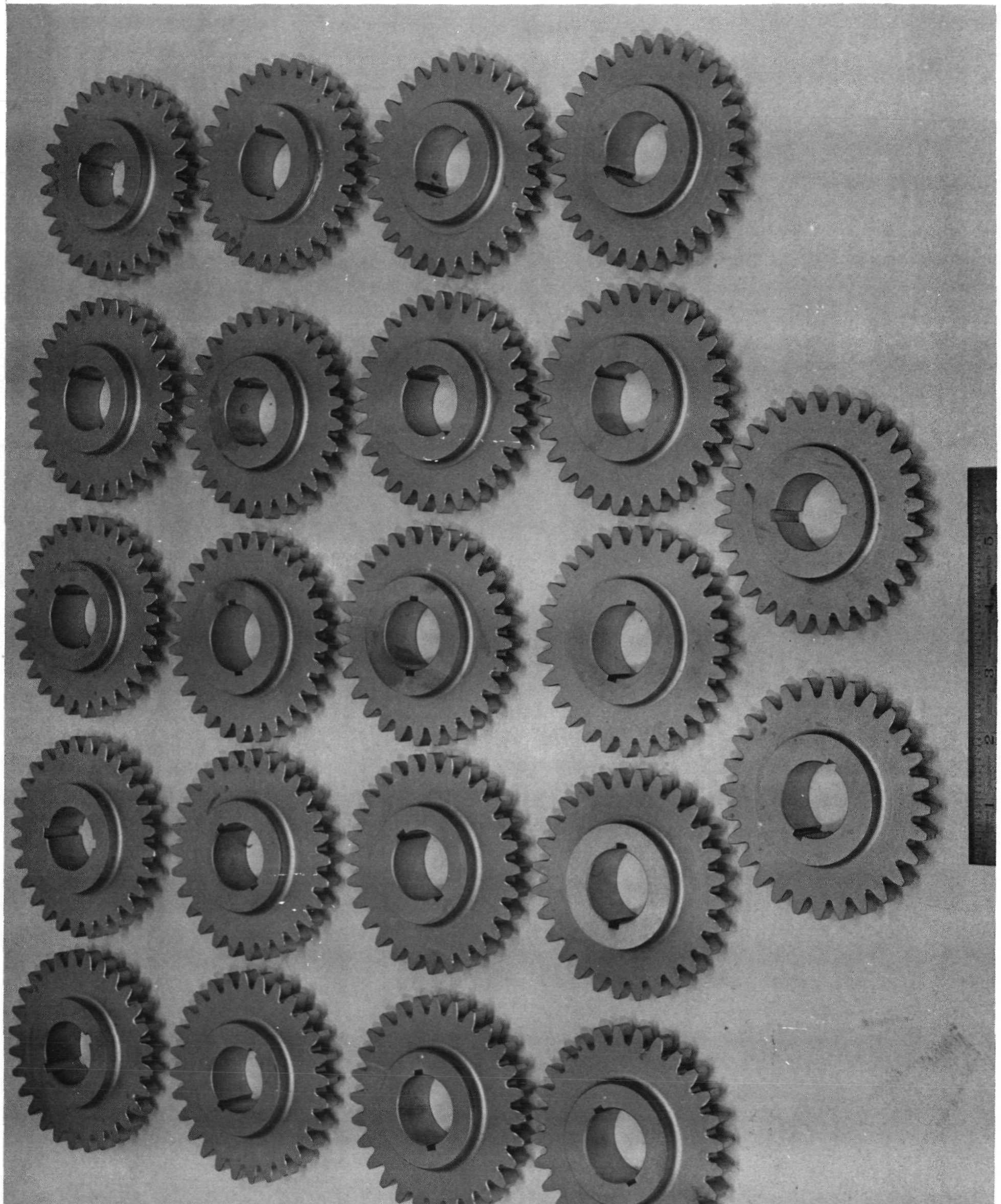


Figure 41 Production Batch of Semi-Finish Machined Standard Forged Gears

Figure 42 Finished Machined Ausformed Gear

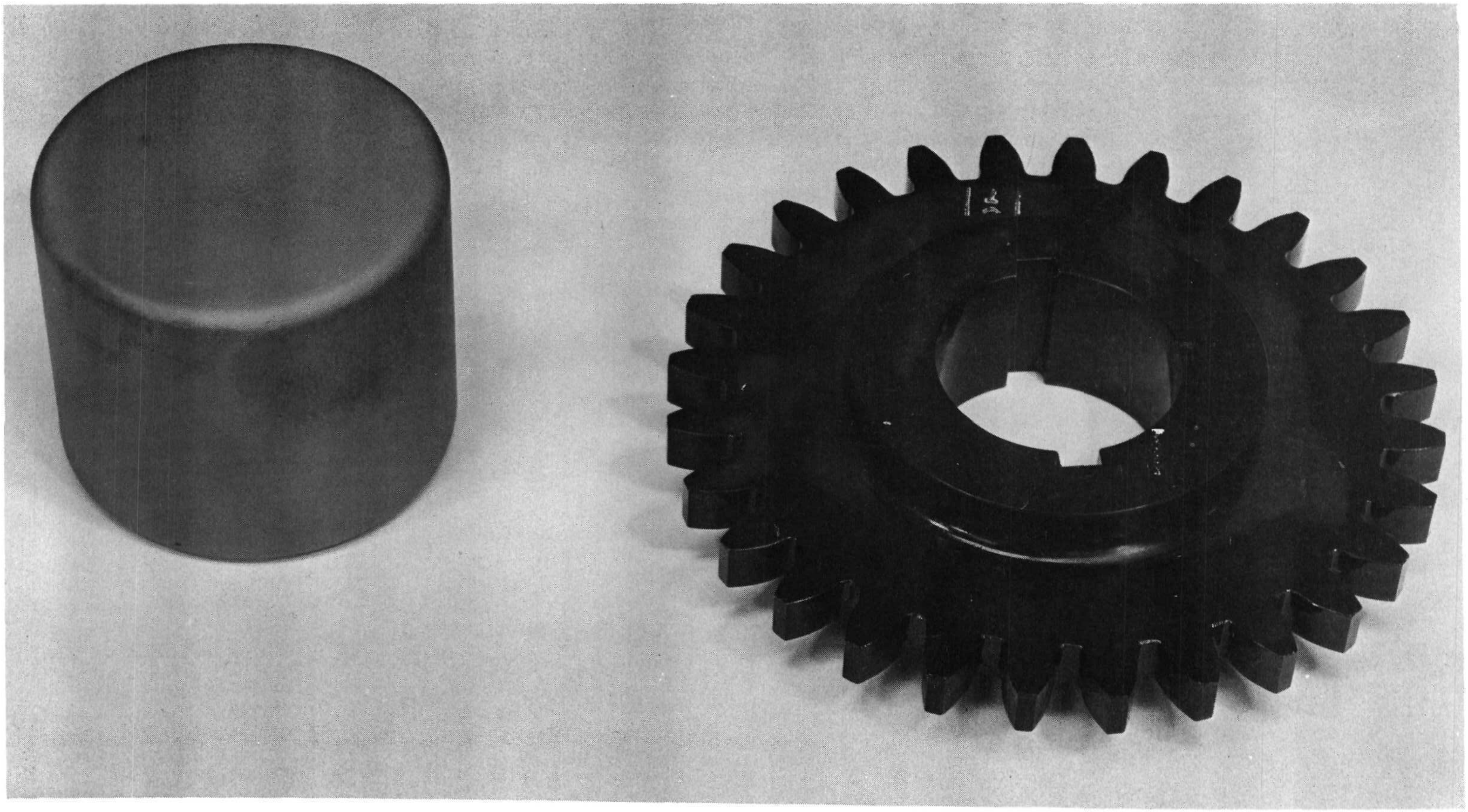


Figure 43 Starting Preform and Finish Machined Ausformed Gear

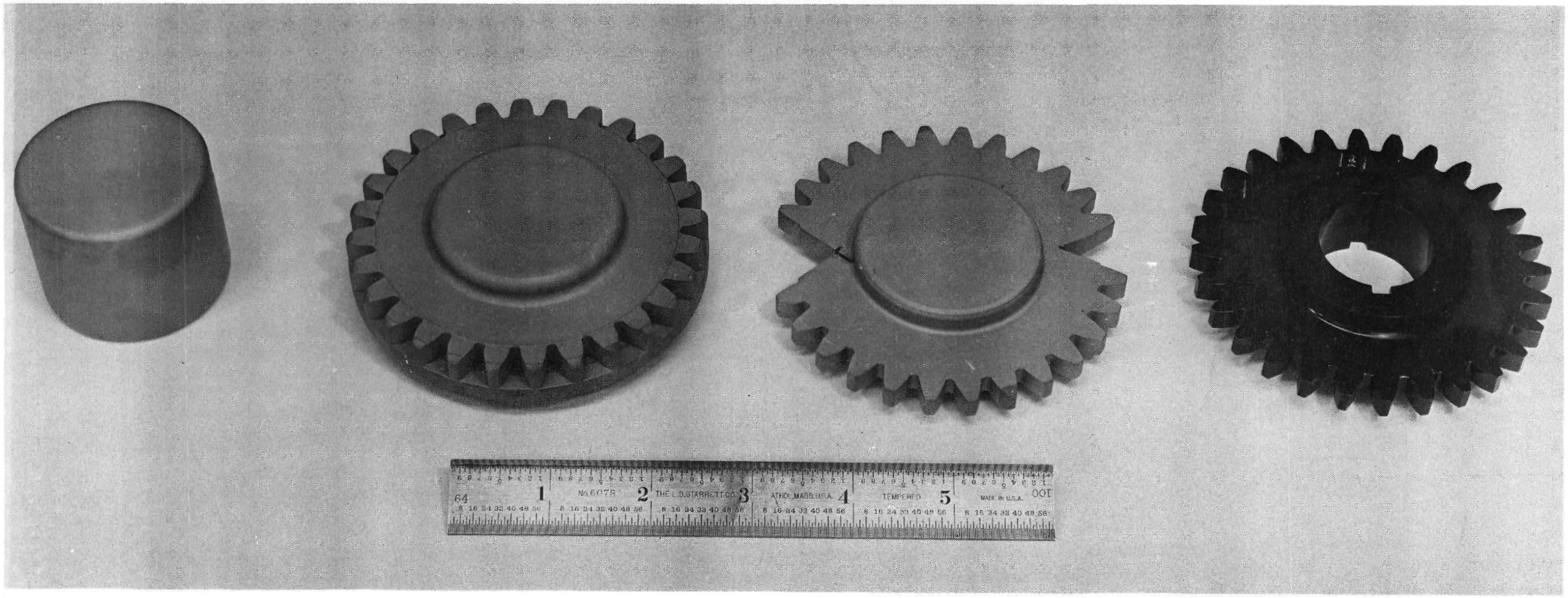


Figure 44 The Four Major Operations in the Production of Ausformed Gears. From Left to Right: Preform, As-Forged, Rough Machined and Finish Machined. (Note: Sections for Metallurgical Examination were Taken From The Partially Finished Gear

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12.0 <u>A P P E N D I X   I</u>

FINAL REPORT - HIGH CONTACT RATIO

SPUR GEAR DESIGN STUDY

VERTOL DIVISION • BOEING CENTER

8-1132-8001
7 July 1971

General Electric Company
Aircraft Engine Group
Cincinnati, Ohio 65225

Attention: Mr. R. Forrester

Subject: Purchase Order No. 200-I-14D46790, Analytical Design of Ausformed High Contact Ratio Spur Gears: Submittal of Final Report

Enclosure: Subject Final Report D210-10310-1 (5 copies)

Gentlemen:

In accordance with the requirements of subject contract, the Contractor forwards herewith, as the Enclosure, the Final Report. Submittal of this Final Report constitutes completion of performance of the contract.

Very truly yours,

THE BOEING COMPANY
Vertol Division

H. D. Fowler
Contract Administrator

HDF/md

REV LTR

THE BOEING COMPANY

VERTOL DIVISION · MORTON, PENNSYLVANIA

CODE IDENT. NO. 77272

NUMBER D210-10310-1

TITLE NASA - LEWIS AUSFORMED HIGH CONTACT RATIO SPUR GEAR DESIGN PROJECT

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MODEL ______ CONTRACT General Electric Company Order No. 200-I-14D46790

ISSUE NO. ______ ISSUED TO: ______

PREPARED BY R. J. Drago DATE 7/1/71
R. J. Drago

APPROVED BY A J. Lemanski DATE 7/1/71
A. J. Lemanski

APPROVED BY ______ DATE ______

APPROVED BY ______ DATE ______

FORM 46280 (3/67) SHEET

REPORT

SUBJECT: General Electric Company Order No. 200-I-14D46790
NASA - Lewis Ausformed High Contact Ratio
Spur Gear Design Project

REFERENCE: Investigation of Increased Load Capacity
of Spur and Helical Gears with
Increased Contact Ratio - October 1970

ENCLOSURES:
(1) Spur Gear Geometry - Computer Output
(2) Transverse Section Tooth Plot - Computer Output
(3) Plot of Bending Stress vs. Pinion Torque
(4) Plot of Pitch Line Contact Stress vs. Pinion Torque
(5) Mesh Kinematics Plots - Computer Output
(6) Involute Profile Modification Chart

A computer analysis of the subject gear set has been completed based on the following initial data:

Center Distance	-	3.500 Inch
Pinion Speed	-	10,000 RPM
Actual Face Width	-	0.250 Inch
Effective Face Width	-	0.100 Inch
Diametral Pitch	-	8.000

The analysis was accomplished in four distinct steps: Basic Geometry Optimization, Strength and Durability Analysis, Mesh Kinematics Analysis, and Profile Modification. The load sharing spectrum developed from the strain gaging conducted during the test program reported in the reference was utilized in this design effort. The results of each design step are summarized as follows:

Basic Geometry Optimization

Boeing-Vertol computer program "HCR" was utilized to define the optimum basic geometry of the gear set. Input to this program includes number of teeth, diametral pitch, minimum topland desired, minimum contact ratio desired, and the applicable tolerances. Several diametral pitches were considered in the range of 8-14. The 8 pitch design had a roll angle of less than 5° at the lowest point of contact, which produces quite unsatisfactory contact conditions both from a pitting and scoring standpoint. The coarsest pitch which has a suitable roll angle at the lowest point of contact is 11.14286. The basic geometry was then optimized at this pitch.

Strength and Durability Analysis

The bending and contact stresses as well as a complete geometric description of the resultant mesh were obtained by use of computer programs R23 and SPUR. Complete tooth geometry data is shown in

Enclosure (1). An automatic data plotter was utilized in conjunction with Program R23 to produce the tooth plot shown in Enclosure (2). Enclosures (3) and (4) present bending stress and contact stress, respectively, as a function of pinion torque. It should be noted at this point that terms such as "load in pounds per inch of face", "unit load", etc. have an extirely different interpretation when applied to high contact ratio gearing, since there are always at least two pairs of teeth in contact.

Mesh Kinematics

Enclosure (5) presents plots of the various kinematic parameters of the mesh at a speed of 10,000 rpm. The abscissa on each plot is the adjusted pinion roll angle which is defined as follows:

$$\theta_A = \theta_P - \theta_I$$

where θ_A = adjusted roll angle - degrees

θ_P = roll angle at pitch point - degrees

θ_I = roll angle at I^{th} point on profile - degrees

A brief description and interpretation of each plot follows:

Sliding Velocity - Sliding velocity is a relative measure of the heat generated during the meshing cycle. While high sliding generally indicates high heat generation, high contact ratio designs generally are lightly loaded in the region of highest sliding so that heat generation and efficiency are both equal to and in many cases better than standard involute designs.

<u>Entraining Velocity</u> - The entraining velocity is a measure of the rate at which fresh lubricant is brought into the contact zone to provide cooling and separation of the mating surfaces. Higher values of entraining velocity indicate a rapid replenishment of the lubricant in the contact area. The entraining velocity for this design is greater than 1200 in/sec indicating suitable entraining conditions.

<u>Slide/Entraining Ratio</u> - Since the sliding and entraining velocities are directly opposite in effect but similar in origin, it is natural to form this ratio as a measure of their joint effect. A high value generally indicates greater net heating, while a low value indicates good lubricant flow and lower heating.

<u>Specific Sliding Ratio</u> - This ratio is formed by dividing the instantaneous sliding velocity by the instantaneous rolling velocity at a given point on the profile. This quantity provides additional insight into the effect of sliding velocity by eliminating the effect of rotational speed. Thus, the effectiveness of different designs operating at various speeds may be easily compared. The slope of this curve in the dedendum

region is typical of high contact ratio designs. This results from extending the profile towards the base circle. A relatively high slope is not desirable for standard designs. However, experimental test results indicate that a high slope does not adversely effect a high contact ratio design as compared to a standard design.

Profile Modification

To minimize interference in the mesh, the true involute profile must be modified to account for tooth deflection under load. A given profile modification is optimum for only a limited range of loads and speeds. The profile modification shown in Enclosure (6) has been designed for a pinion torque level of approximately 300 inch-lb.

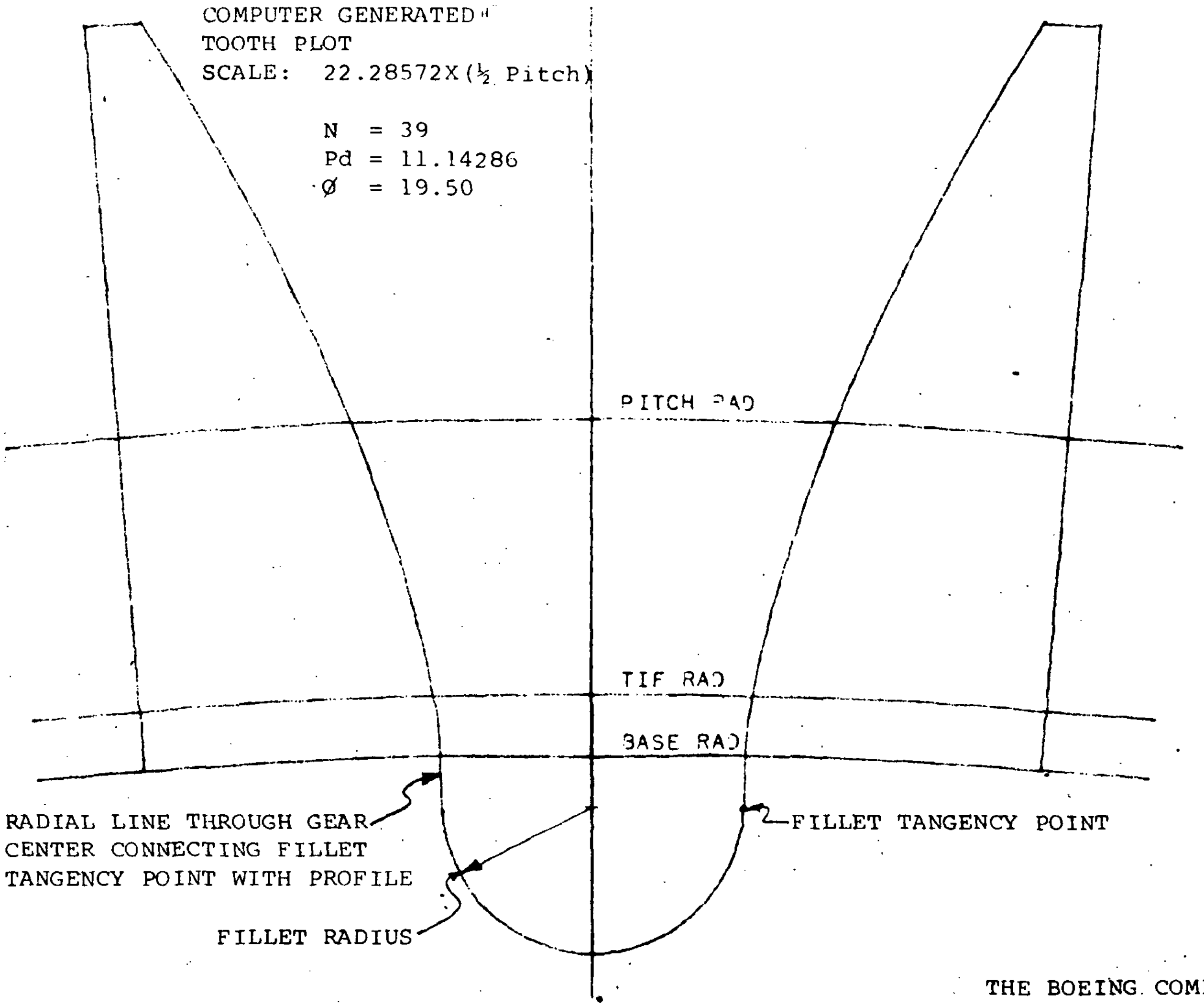
SPUR GEAR STRENGTH ANALYSIS

	PINION		EXTERNAL GEAR	
	MINIMUM	MAXIMUM	MINIMUM	MAXIMUM
NUMBER OF TEETH	39		39	
OUTSIDE RADIUS	1.8719	1.8733	1.8719	1.8738
TOP LAND (INCL. E.B.)	0.01222	0.02541	0.01222	0.02326
EDGE BREAKS	0.0050	0.0100	0.0050	0.0100
BREAK RADIUS	1.8618	1.8688	1.8618	1.8688
FACE WIDTH	0.10000		0.10000	
TRUE INVOLUTE FORM CLEARANCE	0.00500		0.00500	
STD.APC TOOTH THICKNESS	0.13797	0.13897	0.13797	0.13897
PRESSURE ANGLE		19.49998		
CENTER DISTANCE		3.50000		
DIAMETRAL PITCH		11.14286		
PITCH RADIUS	1.7500		1.7500	
OPR.APC TOOTH THICKNESS	0.13797	0.13897	0.13797	0.13897
PRESSURE ANGLE		19.50009		
CENTER DISTANCE		3.50000		
DIAMETRAL PITCH		11.14286		
PITCH RADIUS	1.7500		1.7500	
PROFILE CONTACT RATIO	2.1004 MIN		2.1568 MAX	
BACKLASH AT OPER. C.D.		0.00400 TO 0.00600		
TORQUE	300.0000		300.0000	
BASE RADIUS	1.64962		1.64962	
TRUE INVOLUTE FORM RADIUS	1.66993	1.67259	1.66993	1.67259
ROLL ANGLE AT LAST POINT OF CONT	10.07427	10.59509	10.07427	10.59509
MEASURING PIN DIAMETER	0.174540		0.174540	
MEASUREMENT OVER PINS	3.77656	3.77890	3.77656	3.77890
PIN CLEARANCE OVER O.R.	0.01589	0.01906	0.01589	0.01906
RADIUS TOOTH BECOMES POINTED	1.903	1.904	1.903	1.904
STD.ADDENDUM	0.12185	0.12385	0.12185	0.12385
DEDENDUM	0.15165	0.15915	0.15165	0.15915
OPR.ADDENDUM	0.12185	0.12385	0.15165	0.15915
DEDENDUM	0.12185	0.12385	0.15165	0.15915
WHOLE DEPTH	0.27550	0.28100	0.27550	0.28100
ROOT RADIUS	1.5908	1.5983	1.5908	1.5983
FILLET TANGENCY RADIUS	1.6345	1.6427	1.6345	1.6427
FILLET RADIUS	0.0443	0.0449	0.0443	0.0449
CO= 1.0000 CV= 1.0000 CM= 1.0000 CS= 1.0000 CF= 1.0000				
LOAD ANGLE	17.2412		17.2412	
TANGENTIAL LOAD		108.631		
LOAD RADIUS	1.7272		1.7272	
FILLET RADIUS	0.0447		0.0447	
X-BAR	0.0714		0.0714	
H	0.1137		0.1137	
TOOTH THK.AT C.S.	0.1802		0.1802	
STRESS CONC. FACTOR	1.7066		1.7066	
FORM FACTOR	0.5706		0.5706	
GEOMETRY FACTOR	0.3343		0.3343	
BENDING STRESS	36206.02		36206.02	
GEOMETRY FACTOR		0.07866		
PITCH LINE CONTACT STRESS		144471.20		
ROOT CLEARANCE	0.02780	0.03730	0.02780	0.03730

PREPARED BY: THE ADVANCED DRIVE SYSTEMS TECHNOLOGY DEPARTMENT
THE BOEING COMPANY - VERTOL DIVISION

Enclosure (2)

NASA - LEWIS AUSFORMED HCR
SPUR GEAR DESIGN PROJECT



THE BOEING COMPANY
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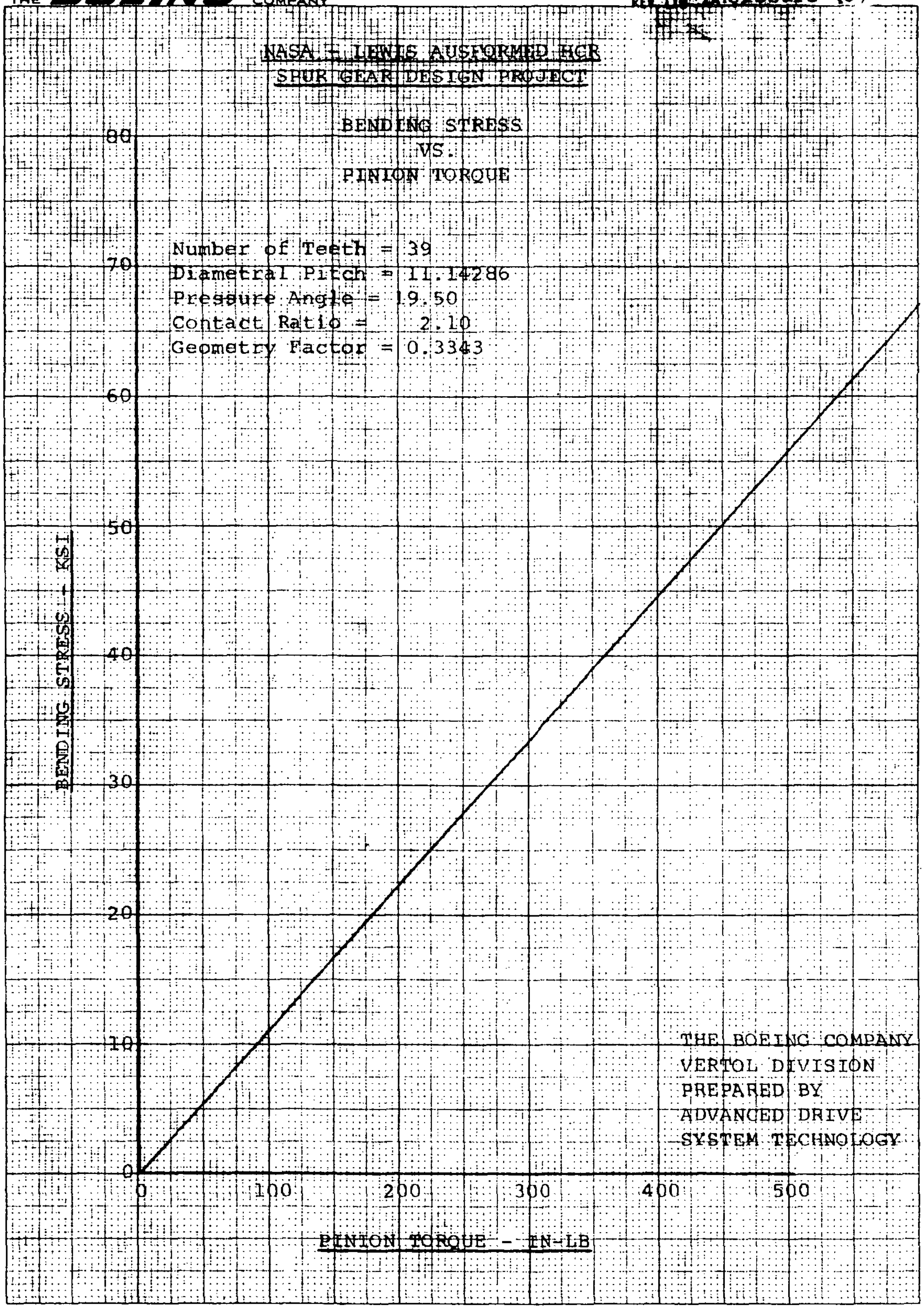
SYSTEM TECHNOLOGY


NASA - LEWIS AUSFORMED HCR
SPUR GEAR DESIGN PROJECT
BENDING STRESS
VS.
PINION TORQUE
Number of Teeth = 39
Diametral Pitch = 11.14286
Pressure Angle = 19.50
Contact Ratio = 2.10
Geometry Factor = 0.3343
BENDING STRESS - KSI
80
70
60
50
40
30
20
10
0
0
100
200
300
400
500
PINION TORQUE - IN-LB
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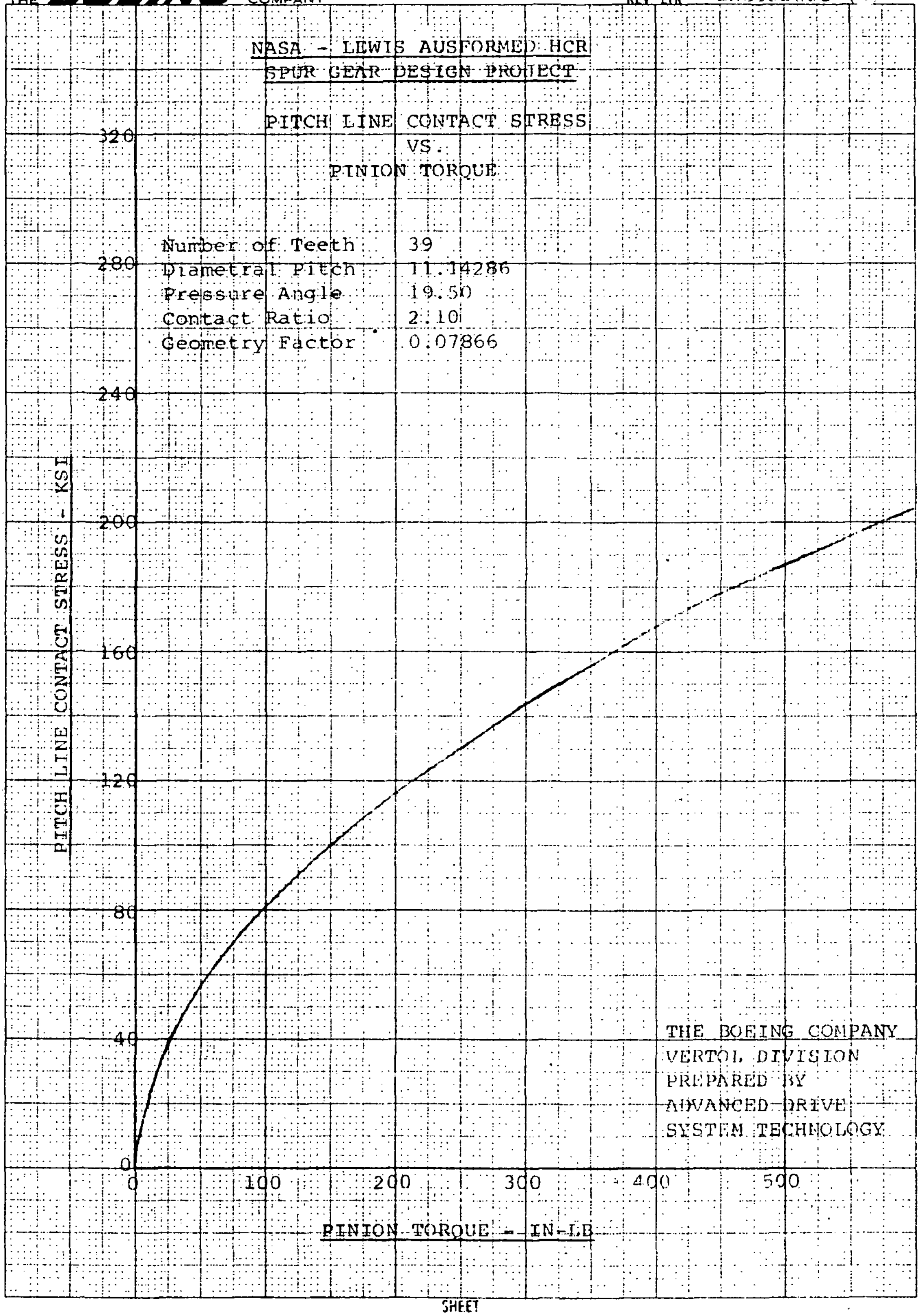
SHEET


NASA - LEWIS AUSFORMED HCR
SPUR GEAR DESIGN PROJECT
PITCH LINE CONTACT STRESS
VS.
PINION TORQUE
Number of Teeth 39
Diametral Pitch 11.14286
Pressure Angle 19.50
Contact Ratio 2.10
Geometry Factor 0.07866
320
280
240
200
160
120
80
40
0
PITCH LINE CONTACT STRESS - KSI
0
100
200
300
400
500
PINION TORQUE - IN-LB
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Enclosure (6)

INVOLUTE PROFILE MODIFICATION CHART

OUTSIDE DIAMETER BREAK (30.87°)
(-0.0005) (-0.0009)

CONTROL POINT NO. 1 (26.00°)
(0.0000) (-0.0003)

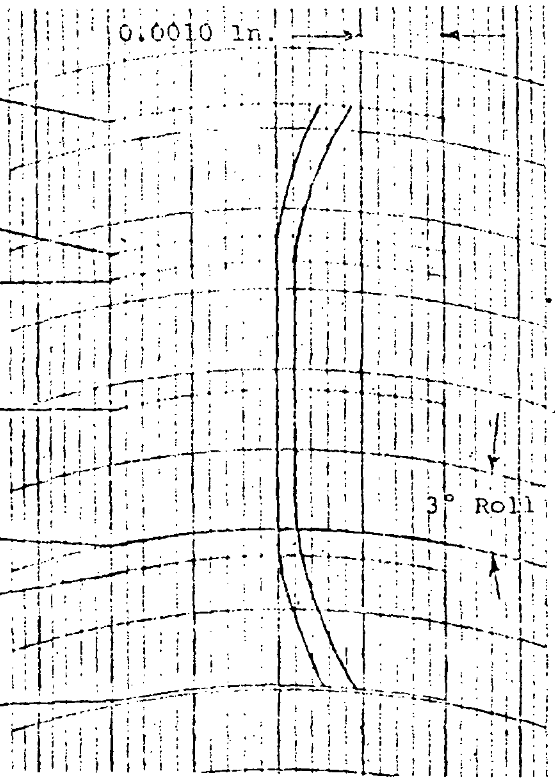
CONTROL POINT NO. 2 (25.00°)
(0.0000) (-0.0002)

PITCH DIAMETER (20.29°)
(0.0000) (-0.0002)

CONTROL POINT NO. 3 (15.00°)
(0.0000) (-0.0002)

CONTROL POINT NO. 4 (14.00°)
(0.0000) (-0.0003)

FORM DIAMETER (9.04°)
(-0.0005) (-0.0009)

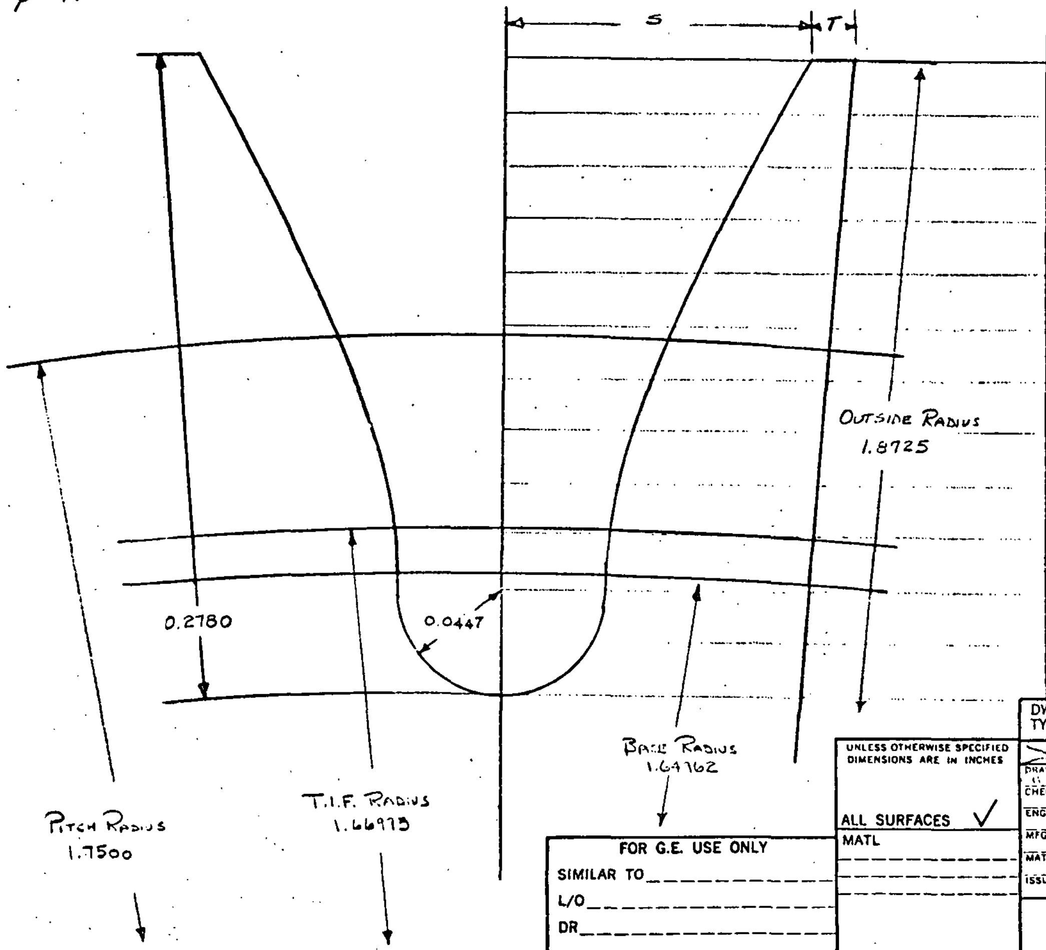


NOTE

Profile shape within the tolerance band shall be a smooth and gradual convex curvature. No steps or grooves permitted. Maximum waviness shall not exceed 0.000025".

The Boeing Company
Vertol Division
Prepared by
Advanced Drive
System Technology.

Scale : 22.23572 x (½ Pitch)
N: 39
Pd: 11.14286
ø: 19.50



Y^*	X_S	X_T
1.8725	0.1339	0.0168
1.8485	0.1199	0.0289
1.8245	0.1068	0.0401
1.8035	0.0962	0.0491
1.7790	0.0849	0.0594
1.7583	0.0758	0.0659
1.7373	0.0677	0.0723
1.7132	0.5944	0.0786
1.6891	0.0526	0.0836
1.6681	0.0479	0.0866
1.6472	0.0447	0.0877
1.6244	0.0421	0.0957
1.591	0.0019	0.1295

* Y Co-ordinate taken from Geometric Center of Gear

REVISIONS			
LTR	DESCRIPTION	DATE	APPROVED

UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN INCHES

ALL SURFACES ✓

MATL

FOR G.E. USE ONLY
SIMILAR TO
L/O
DR

DWG TYPE

SIGNATURES	MO-DA-YR
DRAWN	7/14/71
CHECKED	
ENGR	
MFG	
MATL	
ISSUED	

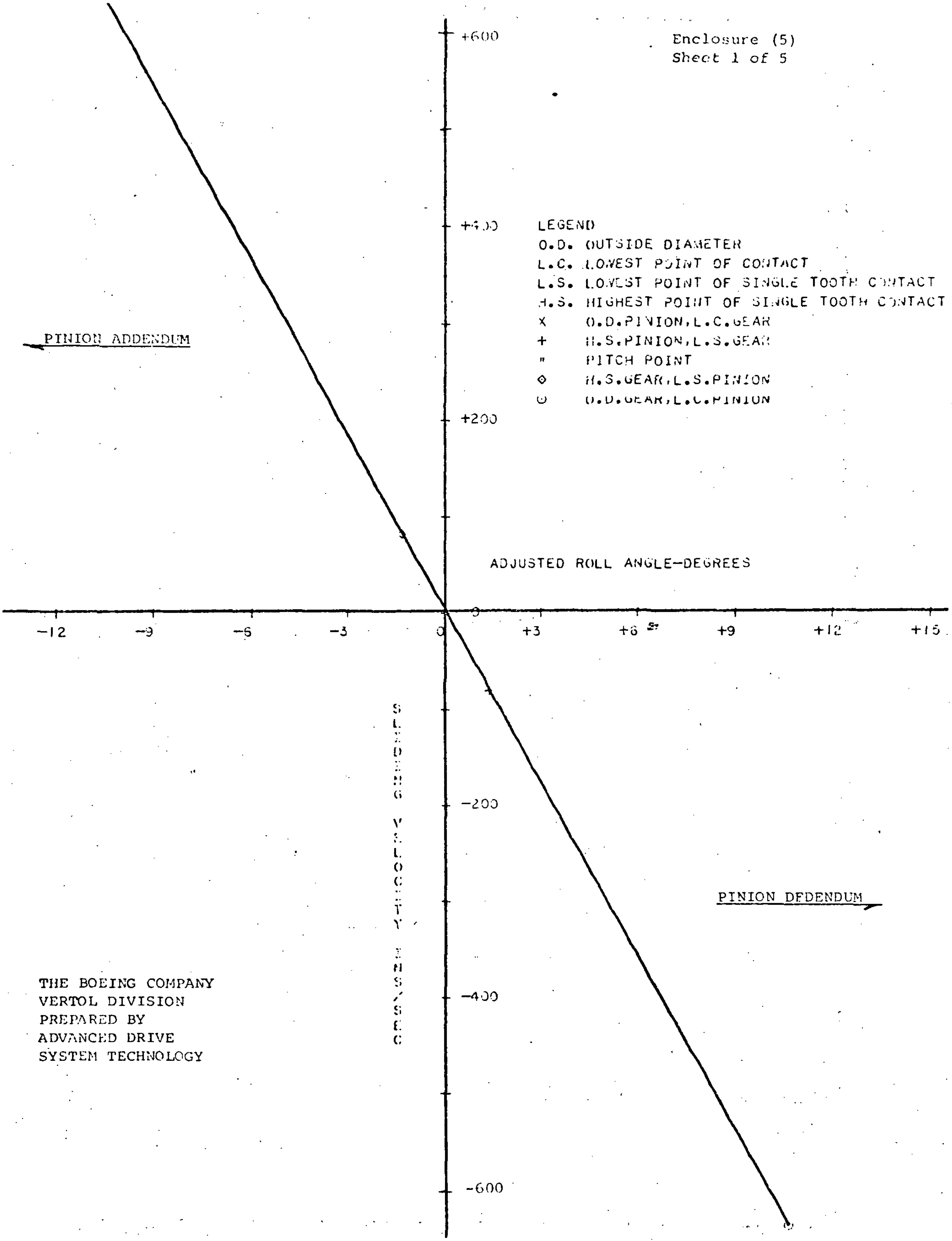
GENERAL ELECTRIC
FLIGHT PROPULSION DIVISION — CINCINNATI, OHIO 45215, U.S.A.

High Contact Ratio Hobformed Gear, - NASA 3-15338

SIZE	CODE IDENT NO.	DWG NO.
B		3-15338-1

SCALE | WT CALC ACTUAL | SHEET

.50 1.00


+600
+400
+200
-200
-400
-600
LEGEND
O.D. OUTSIDE DIAMETER
L.C. LOWEST POINT OF CONTACT
L.S. LOWEST POINT OF SINGLE TOOTH CONTACT
H.S. HIGHEST POINT OF SINGLE TOOTH CONTACT
X O.D.PINION,L.C.GEAR
+ H.S.PINION,L.S.GEAR
" PITCH POINT
◇ H.S.GEAR,L.S.PINION
O O.D.GEAR,L.C.PINION
PINION ADDENDUM
ADJUSTED ROLL ANGLE-DEGREES
-12
-9
-6
-3
0
+3
+6
+9
+12
+15
SLIDING VELOCITY INS/SEC
PINION DEDENDUM
THE BOEING COMPANY
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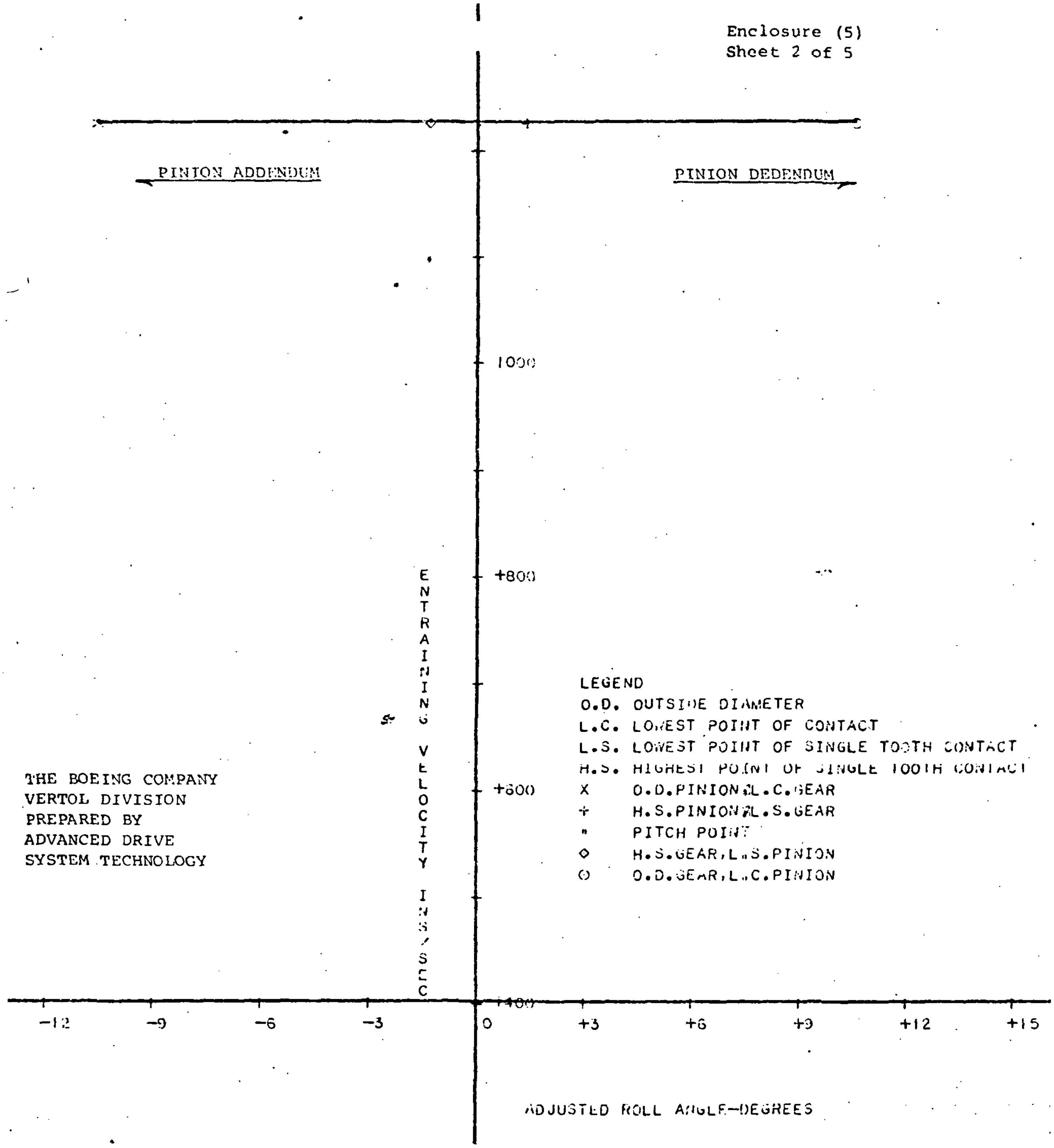
SYSTEM TECHNOLOGY


PINION ADDENDUM
PINION DEDENDUM
1000
+800
+600
+400
ENTRAINING VELOCITY INS/SEC
LEGEND
O.D. OUTSIDE DIAMETER
L.C. LOWEST POINT OF CONTACT
L.S. LOWEST POINT OF SINGLE TOOTH CONTACT
H.S. HIGHEST POINT OF SINGLE TOOTH CONTACT
X O.D.PINION/L.C.GEAR
+ H.S.PINION/L.S.GEAR
" PITCH POINT
◇ H.S.GEAR,L.S.PINION
○ O.D.GEAR,L.C.PINION
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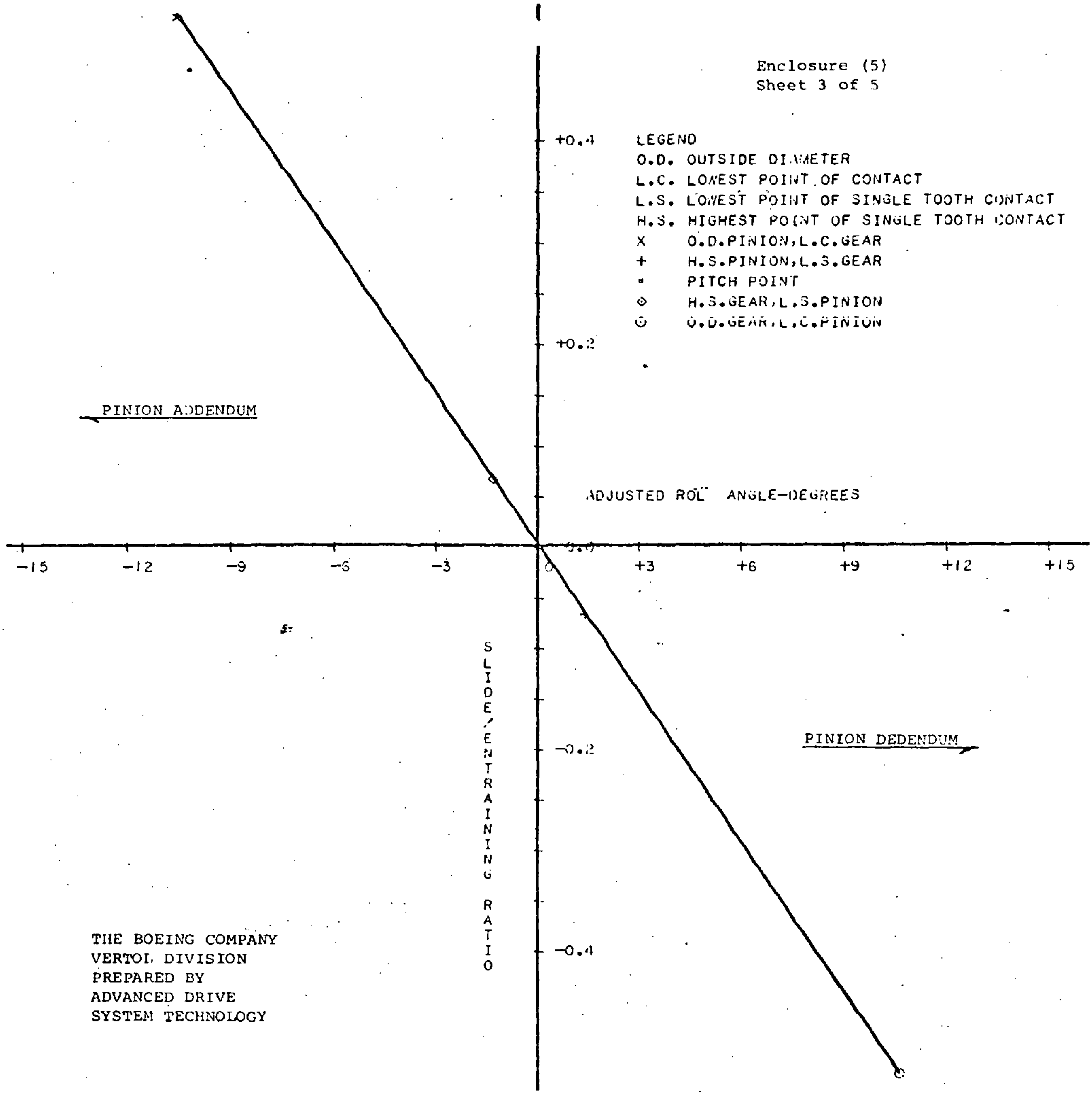
−12
−9
−6
−3
0
+3
+6
+9
+12
+15
ADJUSTED ROLL ANGLE—DEGREES

Enclosure (5)
Sheet 3 of 5



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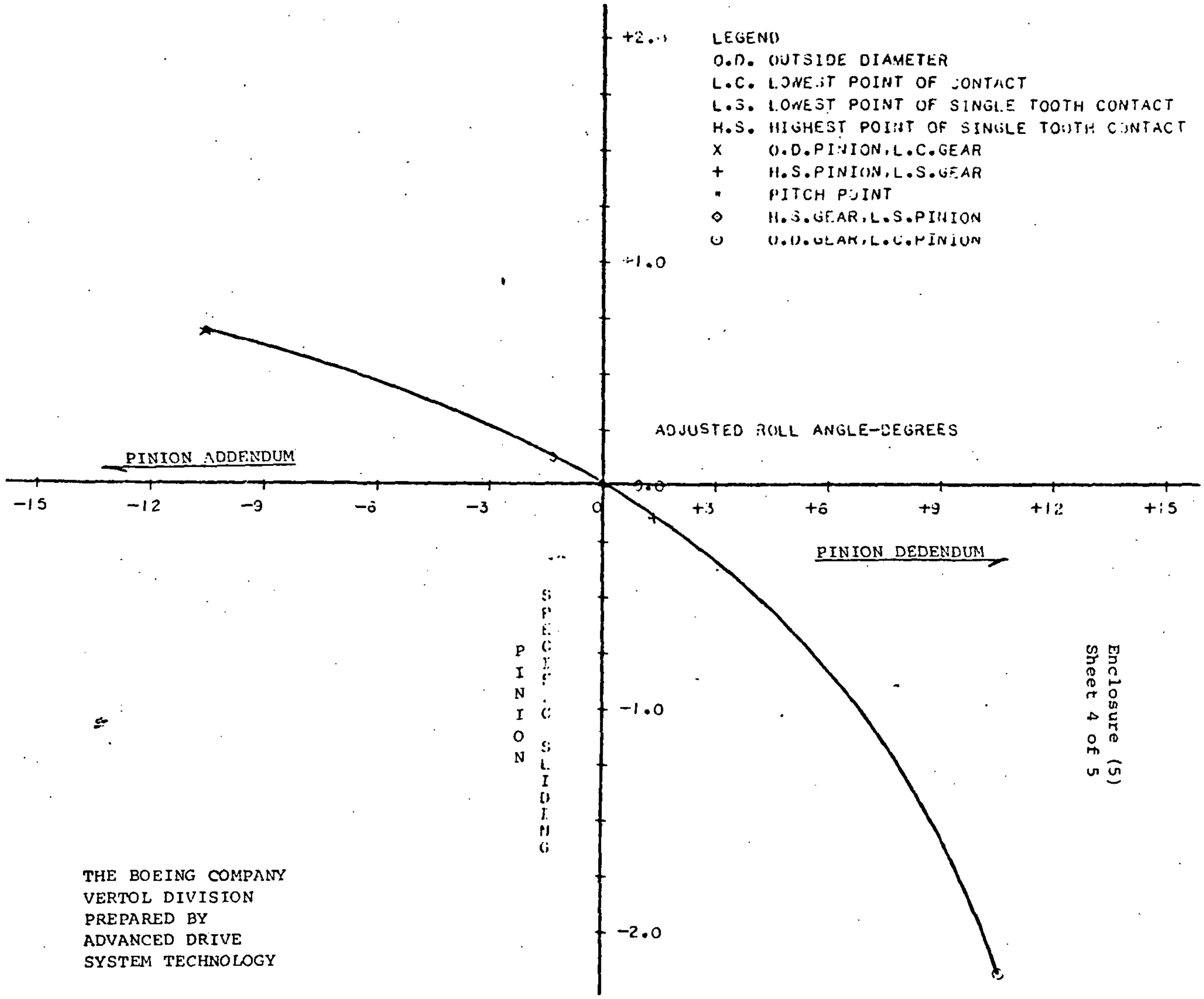

Enclosure (5)
Sheet 4 of 5

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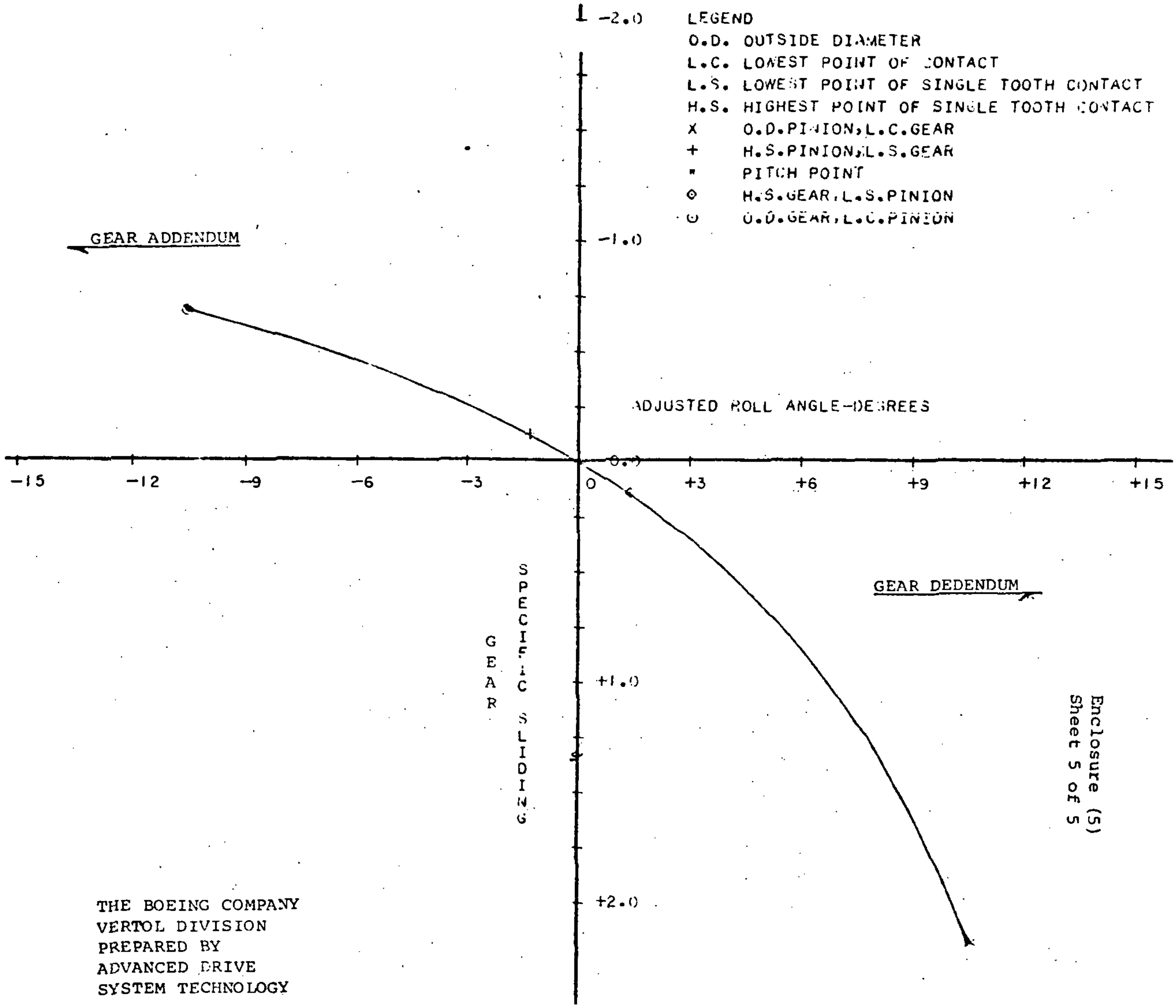

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Enclosure (5)
Sheet 5 of 5

-0.00730419	1.64962196	0.04513550

```
             DELTA B' = 0.027354 RADIANS
GAMMA      = 0.771721 RADIANS
RF         = 0.044919
RX         = 1.641396
             FILLET TAN BELOW BASE CIRC
```

Fillet Radius = 0.04490
Whole Depth = 0.27550
Arc Tooth Thickness = 0.13797
R.J.P.

NOTE:

The coordinates headed X SPACE, Y SPACE include an additional scale factor of 100, required by the data plotter.
The total scale is therefore 100 x 22.28572 = 2228.572.
The coordinates headed X CL TOOTH, Y CL TOOTH are full sized (i.e. Scale = 1X)

R.J.P.

PROGRAM 823 TOOTH BENDING STRENGTH

X SPACE	Y SPACE	X CL TOOTH	Y CL TOOTH
298.53222656	486.22900391	0.01677288	1.87252426
294.52270508	479.87207031	0.01833662	1.86953545
290.54467773	473.51098633	0.01988619	1.86654663
286.59567769	467.14135742	0.02142214	1.86355591
282.66066406	460.77172852	0.02294344	1.86056519
278.79467773	454.39355469	0.02445133	1.85757256
274.94091797	448.01123047	0.02594443	1.85457897
271.11718750	441.62451172	0.02742409	1.85158443
267.32641602	435.23388672	0.02888283	1.84858894
263.56591797	428.83666992	0.03033977	1.84559155
259.83862305	422.43505859	0.03177579	1.84259415
256.14282227	416.03125000	0.03319745	1.83959579
252.47784424	409.61938477	0.03460523	1.83659649
248.84675598	403.20507813	0.03599776	1.83359623
245.24610901	396.78442383	0.03737632	1.83059502
241.67945862	390.35157227	0.03873763	1.82759285
238.14460754	383.93041992	0.04008347	1.82458973
234.64324951	377.49902344	0.04142228	1.82158661
231.17369080	371.06152344	0.04274162	1.81858158
227.73864746	364.61962891	0.04404550	1.81557655
224.33590698	358.17553398	0.04533455	1.81257057
220.96784973	351.72554180	0.04660815	1.80956459
217.63324552	345.27270508	0.04786564	1.80655861
214.33171032	338.61372070	0.04911003	1.80355072
211.06559598	332.15278320	0.05033769	1.80054283
207.83227539	325.68549805	0.05155027	1.79753399
204.63475037	319.41796875	0.05274678	1.79452515
201.47153313	312.94213867	0.05392781	1.79151535
198.34411521	306.46630859	0.05509277	1.78850555
195.25115967	299.98388672	0.05624214	1.78549480
192.19425964	293.50170898	0.05737526	1.78248501
189.17340088	287.01513672	0.05849218	1.77947426
186.18600453	280.52246094	0.05959301	1.77646255
183.23947144	274.02734375	0.06067727	1.77345085
180.32709740	267.52807617	0.06174527	1.77043915
177.45243835	261.02661133	0.06279624	1.76742744
174.61405945	254.52122498	0.06383079	1.76441479
171.81446838	248.01345825	0.06484795	1.76140308
169.05192566	241.49923706	0.06584841	1.75839043
166.32854276	234.98516846	0.06683129	1.75537872
163.64283752	228.46669006	0.06779712	1.75236607
160.99753911	221.94618225	0.06874484	1.74935436
158.39154053	215.42361450	0.06967485	1.74634266
155.82507324	208.89460754	0.07058698	1.74333000
153.29749951	202.36558533	0.07148081	1.74031830

PR GEAR 823 TOOTH BENDING STRENGTH

X SPACE	Y SPACE	X CL TOOTH	Y CL TOOTH
150.81419373	195.83010864	0.07235652	1.73730564
148.37086487	189.29479980	0.07321334	1.73429489
145.96937561	182.75506592	0.07405132	1.73128319
143.61091614	176.21549988	0.07486993	1.72827244
141.29483032	169.66947937	0.07566953	1.72526073
139.02363586	163.12345886	0.07644904	1.72225094
136.79580688	156.57106018	0.07720894	1.71924114
134.61413574	150.02078247	0.07794815	1.71623135
132.47831726	143.46626282	0.07865675	1.71322346
130.38700757	136.90748596	0.07936442	1.71021461
128.34814453	130.34870911	0.08004040	1.70720673
126.35517883	123.78356934	0.08069479	1.70419894
124.41229248	117.22053528	0.08132672	1.70119286
122.52049255	110.65113831	0.08193570	1.69818687
120.68098450	104.08174133	0.08252126	1.69518280
118.89453125	97.51020813	0.08308291	1.69217777
117.16354370	90.93656921	0.08361971	1.68917561
115.48913574	84.35653687	0.08413112	1.68617249
113.87362671	77.77864075	0.08461618	1.68317223
112.31895447	71.19500640	0.08507395	1.68017292
110.82599007	64.61219788	0.08550346	1.67717361
109.45167236	58.02792358	0.08590317	1.67417622
108.04490662	51.43727112	0.08627200	1.67117977 ✓
106.76140987	44.84661865	0.08660805	1.66818619
105.55699131	38.25170698	0.08690966	1.66519260
104.43415833	31.65601458	0.08717261	1.66220188
103.40351868	25.05552673	0.08739537	1.65921307
102.47502136	18.45425415	0.08757228	1.65622711
101.66352844	11.84572437	0.08769679	1.65324306
100.97649043	5.23894215	0.08775645	1.65026293
100.04856873	-19.70181274	0.08771724	1.64728737

DATA ABOVE REFERS TO INVOLUTIAL COORDINATES
DATA BELOW REFERS TO FILLET COORDINATES

100.04136140	-19.96748352	0.08727354	1.63895321
100.00599670	-20.96852112	0.08725309	1.63850403
99.96090698	-21.96954346	0.08723712	1.63805485
99.90579224	-22.97058105	0.08722562	1.63760567
99.84059143	-23.97160339	0.08721864	1.63715553
99.76531982	-24.97264099	0.08721614	1.63670540
99.67993164	-25.97367859	0.08721823	1.63625336
99.58442688	-26.97470093	0.08722478	1.63580322
99.47874451	-27.97573853	0.08723587	1.63535118
99.36286926	-28.97676086	0.08725160	1.63489914
99.23673589	-29.97567749	0.08727193	1.63444805
99.10040283	-30.97669983	0.08729672	1.63399601
98.95373535	-31.97773743	0.08732623	1.63354206
98.79669189	-32.97875977	0.08736032	1.63308907

Fillet And Profile
Connected With
Radial Straight
Line From Gear
center.
Rd

PROGRAM R23 TOOTH BENDING STRENGTH

X SPACE	Y SPACE	X CL TOOTH	Y CL TOOTH
98.62927246	-33.97979736	0.08739907	1.63263512
98.45135498	-34.98083496	0.08744252	1.63218117
98.26295471	-35.98185730	0.08749062	1.63172626
98.06395494	-36.98289490	0.08754349	1.63127136
97.85432434	-37.98391724	0.08760113	1.63081551
97.63398743	-38.98495483	0.08766347	1.63036060
97.40286255	-39.98597717	0.08773071	1.62990379
97.16088857	-40.98701477	0.08780277	1.62944794
96.90794373	-41.98591614	0.08787984	1.62899208
96.64401245	-42.98695374	0.08796179	1.62853527
96.36494226	-43.98799133	0.08804864	1.62807751
96.08265686	-44.98901367	0.08814055	1.62761879
95.78506470	-45.99005127	0.08823752	1.62716103
95.47607422	-46.99107361	0.08833957	1.62670135
95.15553294	-47.99211121	0.08844680	1.62624264
94.82333374	-48.99313354	0.08855921	1.62578297
94.47937012	-49.99417114	0.08867693	1.62532330
94.12351990	-50.99520874	0.08879995	1.62486172
93.75563049	-51.99623108	0.08892834	1.62440109
93.37555458	-52.99726868	0.08906221	1.62393951
92.98316956	-53.99524102	0.08920157	1.62347794
92.57329265	-54.99720764	0.08934653	1.62301636
92.16078186	-55.97822998	0.08949715	1.62255383
91.73040771	-56.99926758	0.08965355	1.62208939
91.28707885	-57.00028992	0.08981562	1.62162685
90.83055115	-59.00132751	0.08998370	1.62116146
90.36059570	-60.00236511	0.09015769	1.62069798
89.87709045	-61.00338745	0.09033787	1.62023258
89.37973022	-62.00442505	0.09052420	1.61976624
88.86624717	-63.00544739	0.09071672	1.61930084
88.34262085	-64.00648499	0.09091574	1.61883354
87.80238342	-65.00752258	0.09112120	1.61836720
87.24779419	-66.00854492	0.09133333	1.61789894
86.67706299	-67.00744629	0.09155232	1.61743164
86.09147170	-68.00848389	0.09177610	1.61696243
85.49017334	-69.00752148	0.09201080	1.61649323
84.87272748	-70.01054382	0.09225068	1.61602306
84.23391733	-71.01158142	0.09249618	1.61555290
83.58586365	-72.01260376	0.09275305	1.61508083
82.92559326	-73.01364136	0.09301561	1.61460972
82.23516372	-74.01467896	0.09328598	1.61413670
81.53178406	-75.01570129	0.09356445	1.61366367
80.80984497	-76.01673889	0.09385121	1.61318970
80.06837817	-77.01776123	0.09414649	1.61271572
79.30634961	-78.01879883	0.09445047	1.61224079

PROGRAM R23 TOOTH BENDING STRENGTH

X SPACE	Y SPACE	X CL TOOTH	Y CL TOOTH
78.52772522	-79.01982117	0.09476346	1.61176491
77.72537939	-80.01873779	0.09508580	1.61128902
76.90355601	-81.01976013	0.09541768	1.61081123
76.05635515	-82.02079773	0.09575933	1.61033344
75.19123840	-83.02182007	0.09611130	1.60985374
74.30103357	-84.02285767	0.09647375	1.60937500
73.38432312	-85.02389526	0.09684712	1.60889339
72.44325256	-86.02491760	0.09723192	1.60841179
71.47576904	-87.02595520	0.09762847	1.60792923
70.48080444	-88.02697754	0.09803736	1.60744572
69.45715332	-89.02801514	0.09845906	1.60696030
68.40355445	-90.02905273	0.09889412	1.60647488
67.31860352	-91.03007507	0.09934324	1.60598755
66.20071411	-92.02897644	0.09980720	1.60550117
65.04826355	-93.03001404	0.10028648	1.60501099
63.85931396	-94.03105164	0.10078210	1.60452080
62.63183594	-95.03207397	0.10129493	1.60402870
61.36344919	-96.03311157	0.10182613	1.60353565
60.05165100	-97.03413391	0.10237670	1.60304070
58.69348145	-98.03517151	0.10294801	1.60254383
57.28567927	-99.03620911	0.10354155	1.60204506
55.82435698	-100.03723145	0.10415894	1.60154438
54.30535389	-101.03826904	0.10480219	1.60104275
52.72363281	-102.03929138	0.10547358	1.60053730
51.07333374	-103.04032898	0.10617548	1.60002995
49.34762573	-104.04135132	0.10691124	1.59951973
47.53825904	-105.04026794	0.10768443	1.59900761
45.63534020	-106.04129028	0.10849935	1.59849072
43.62652538	-107.04232738	0.10936171	1.59797096
41.49652100	-108.04336548	0.11027825	1.59744644
39.22560120	-109.04438782	0.11125773	1.59691715
36.78759766	-110.04542542	0.11231206	1.59638023
34.14669359	-111.04644775	0.11345702	1.59583759
31.25149209	-112.04748535	0.11471570	1.59528542
28.02415466	-113.04650769	0.11612320	1.59472179
24.33143615	-114.05166626	0.11773860	1.59413910
22.81326294	-114.41935730	0.11840433	1.59391975
21.29500972	-114.76577759	0.11907083	1.59371090
19.77693176	-115.09670044	0.11973828	1.59351158
18.25275854	-115.37786391	0.12040681	1.59332752
16.74060059	-115.64567566	0.12107611	1.59315205
15.22243309	-115.89221191	0.12174624	1.59298706
13.70426655	-116.11537170	0.12241721	1.59283257
12.18607905	-116.31515503	0.12308902	1.59268856
10.66793633	-116.49154663	0.12376165	1.59255409

PROGRAM R23 TOOTH BENDING STRENGTH

X SPACE	Y SPACE	X CL TOOTH	Y CL TOOTH
9.14976833	-116.64031982	0.12443531	1.59243298
7.63160610	-116.76785278	0.12510973	1.59232140
6.11343765	-116.87411499	0.12578487	1.59221935
4.59526920	-116.95274353	0.12646109	1.59212875
3.07710075	-117.01013184	0.12713808	1.59204865
1.55893230	-117.03138733	0.12781596	1.59197998
0.04076569	-117.05052185	0.12849462	1.59192085

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