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COMPUTER AIDED DESIGN AND MANUFACTURING (CAD/CAM) TECHNIQUES FOR OPTIMUM PREFORM AND FINISH FORGING OF SPIRAL BEVEL GEARS

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In Phase II of this program, spiral bevel gear forging dies were designed and manufactured using the CAD/CAM technique, developed in Phase I. Three series of forging trials were conducted. During the first series of trials, the technological aspects of the forging procedure such as heating, lubrication, billet temperature and cooling were established. During the second series of forging trials 20 gears were forged with a 0.007 inch machining allowance on both sides of the tooth surfaces. These near net forged gears were subsequently

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machined with a single machining operation using a Gleason spiral gear cutting machine. The third series of trials were conducted to forge 20 gears with net teeth dimensions. The dimensional accuracy of the forged gears were evaluated using a computer controlled coordinate measuring machine, manufactured by Zeiss of W. Germany. The results of these measurements illustrated that the teeth dimensions of forged gears were within the tolerances expected and as predicted by the CAD/CAM techniques, developed in this program.

This project was successful in:

a) developing the methodology of CAD/CAM procedures for manufacturing the dies (via EDM) for forging spiral bevel gears

b) demonstrating that precision forging of spiral bevel gears is a practical production technique. Although no detailed economical evaluation was made in this study, it is expected that precision forging offers an attractive alternative to the costly gear cutting operations, for producing spiral bevel gears.

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PREFACE

This report covers the work performed under Phase II of Contract No. DAAK30-79-C-0071 from April 1, 1981, to May 1, 1982. It is published for technical information only and does not necessarily represent the recommendations, conclusions or approval of the Army. This contract with Battelle Columbus Laboratories, Columbus, Ohio, was initiated under the Manufacturing Methods and Technology project "Computer Aided Design and Manufacturing (CAD/CAM) Techniques for Optimum Preform and Finish Forging of Sprial Bevel Gears". It is being conducted under the direction of Mr. Donald Ostberg of the Metals & Welding Subfunction (DRSTA/RCKM) of the U.S. Army Tank-Automotive Command, Warren, Michigan (TACOM). Battelle's Columbus Laboratories is the prime contractor on this program with Eaton Corporation of Cleveland, Ohio, as subcontractor.

At Battelle, Dr. Taylan Altan is program manager and Dr. Aly Badawy is principal investigator. Other Battelle staff, namely Drs. T. Schultes and P. S. Raghupathi also contributed to the program as required.

At Eaton, the principal investigator and the project engineers are Messrs. A. L. Sabroff, R. Douglas, and G. Horvat, respectively. Other Eaton staff, namely Messrs. G. Vollmer, R. Hoffman, J. Seaver, T. Johnston, R. Fritch, W. Litzenberg, and others also contributed to the program.

INTRODUCTION

In industrial practice, attempts are continuously made to introduce improved manufacturing methods to reduce production and life cycle costs. Close tolerance forging of spiral bevel gears, requiring only a single or no finish machining operation, offers considerable advantages over machining because this method of manufacture: (a) reduces material losses and machining costs and (b) increases the fatigue life of gears up to 30 percent.

A few companies around the world are able to produce spiral bevel gears by precision forging. However, the development of the process for each new gear design requires considerable trial and error. Thus, application of computer techniques to the design and manufacture (CAD/CAM) of the gear forging dies represents an attractive alternative. Therefore, in this program, methods were developed to apply existing advanced computer aided design and manufacturing (CAD/CAM) technology (finite element, metal forming and heat transfer analysis) to gear forging die design and manufacture. Gear forging dies were designed and manufactured according to the data supplied by the output of the CAD procedure, thus, the CAD and CAM processes were integrated. The results of the CAD/CAM techniques were evaluated for a given spiral bevel gear/pinion set by designing and manufacturing the forging dies via CAD/CAM. Three series of forging trials were conducted. During the first series, the technological details of the forging procedure such as heating, lubrication, part transfer and cooling were established. During the second series of trials, 20 gears were produced with gear teeth forged to near net dimensions. These gears were subsequently machined with a single machining operation. In the third series of trials, 20 spiral bevel gears were forged with net teeth dimensions. Thus, the gear-pinion sets were obtained by machining only the back side of the forged gears and by machining the matching pinions.

The project was successful in

(a) developing the details of CAD/CAM for making the forging dies,

(b) forging gears with near net and net teeth surfaces,

(c) demonstrating the practicality and economics of precision forging spiral bevel gears.

It is expected that the techniques demonstrated by this project can be used for manufacturing, on a production basis, spiral bevel gears by forging. With these techniques, it is only necessary to finish machine the backside, not the teeth, of the forged gears. The matching pinions are still to be manufactured conventionally by gear cutting. Thus, by eliminating the tooth cutting process for the gears, which represents the costliest operation in producing matching gear-pinion sets, considerable savings in manufacturing costs can be expected. In addition, existing data on forged bevel gears illustrates that forged gears are superior, in terms of fatigue life and load carrying capability, to cut gears. Consequently, a similar improvement in performance can also be expected from forged spiral bevel gears.

PURPOSE AND OBJECTIVES

The overall objective of this program is to develop a general purpose computer-aided design and manufacturing (CAD/CAM) technique for producing precision-forging dies for families of spiral bevel gears. Thus, the specific objectives of this program are:

a) Optimize the design, manufacture, and life of dies used in precision-gear forging by CAD/CAM techniques;

b) Reduce the cost of die and process development for precision forging of spiral-bevel gears of different sizes by CAD/CAM techniques;

c) Make the CAD/CAM system sufficiently flexible so that a) it can be used for a family of bevel gears and b) it can easily be introduced into production forge shops.

In Phase I of the project, the CAD program for designing spiral bevel gear forging dies was completed. In Phase II (the topic of this report) the CAM techniques for manufacturing the forging dies were established using the output of the CAD program developed in Phase I. This report covers the details of Phase II and illustrates the integration of the CAD and CAM processes into one system.

BACKGROUND

All significant manufacturing methods and technology programs conducted on gear forging in the U.S., have been sponsored by the U.S. Army. A brief summary of these programs is given in the Phase I report of this project(1). Two major studies, one using a High Energy Rate Forging (HERF) machine and the other using a mechanical forging press, were conducted for precision forging spiral bevel gears. Both projects developed valuable detailed information but neither resulted in a production process. However, there are companies in Japan and W. Germany that net or near net forge spiral bevel gears on a production basis.(1)

Precision warm or hot forging of bevel gears is a well accepted production method in the U.S. as well as abroad. In a typical operation, slugs are sawed from peeled, machined or centerless-ground hot-rolled bar to close weight tolerances. They are heated by induction under neutral atmosphere to 900° to 2,200° F (482° to 1,204° C). In some cases, the slugs may be lubricant coated prior to heating. Forging is usually done in two operations: one blocker and the other finisher forging.

The forged parts are cooled slowly and uniformly either under air flow or by placing the teeth side of the gears into a sand-graphite mixture. Forging flash and the back side of the gears are machined by holding the gear on the pitch line in special fixtures. A negative of the tooth form locates the component insuring correct relationship between machined faces, center holes, and the forged teeth. Machined gears are inspected using special fixtures. If extreme accuracy is required, a hydraulic press cold coining operation is performed on the surface of the teeth. The key to successful precision forging is the design and manufacture of the dies to precise dimensions. Corrections in the gear teeth impressions in the die must be made to account for shrinkage, thermal, and elastic deflections and to give long die life. The die cavity is made by EDM using an exact electrode, with appropriate dimensional corrections.

The extension of the technology, used for precision forging straight bevel gears, to forging of spiral bevel gears is not straightforward. The spiral tooth shape requires much more careful die correction and die design engineering than that necessary for forging of straight bevel gears.

PROGRAM HIGHLIGHTS

Application of CAD/CAM to Forging

In recent years, Computer Aided Design and Manufacturing (CAD/CAM) techniques have been applied to die design and manufacture for forging (a) rib-web type aircraft structural parts(2), (b) track shoes for military vehicles(3), and (c) precision turbine and compressor blades(4). The experience gained in all these applications indicates that a certain overall methodology is necessary for CAD/CAM of dies for precision and/or near net shape forging. This approach indicates that the necessary input to the CAD/CAM system are:

(a) Geometric description of the forging
(b) Data on billet material under forging conditions (billet and die temperatures, and rate and amount of deformation)
(c) Friction coefficient to quantify the friction shear stress at material and die interface
(d) Forging conditions, i.e., temperatures, deformation rates, die lubricants, method of heating the billets, and suggested number of forging operations.

With these input data, a preliminary design of the finish forging die can be made. Next, stresses necessary to finish forge the part and temperatures in the forging and the dies are calculated. The temperature calculations take into account the heat generated due to deformation and friction and the heat transfer during the contact between the hot forging and the cooler dies. Thus, the elastic die deflections due to temperatures and stresses can be estimated and used to predict the small corrections necessary on the finish die geometry. The estimation of die geometry corrections is necessary for obtaining close tolerance forgings and for machining the finish dies to the exact dimensions.

The overall procedure described above, has been applied to CAD/CAM of spiral bevel gears and is described in detail in the Phase I final report of this project.(1)

Program Outline

The program is being conducted in three phases:

- Phase I - Computer Aided Design (CAD) of forging dies. This Phase was successfully completed and the results are given in Phase I final report.(1)

- Phase II - Computer Aided Manufacturing (CAM) of the forging dies (from rough billet) and demonstration of the effectiveness of CAD/CAM by forging 20 spiral bevel gear sets. The present report describes the work accomplished in Phase II.
- Phase III - Application of CAD/CAM techniques to actual production of bevel gears (spiral or straight). This phase has not yet started.

PROGRAM APPROACH

Summary of Phase I Work

In Phase I, the CAD (Computer Aided Design) of spiral bevel gear forging dies has been carried out(1). All of the Phase I work was conducted at Battelle with some input from Eaton Corporation and Mr. M. L. Baxter, subcontractor and consultant to the program, respectively. Phase I was conducted by carrying out three major tasks:

Task 1: Transformation of Dimensional Data into Computer-Compatible Digital Data
Task 2: Computer Aided Design (CAD) of Forging Dies
Task 3: Development of the Interactive Computer Aided Design System.

Each Phase I task is described briefly in the following paragraphs.

Task 1. Transformation of Dimensional Data into Computer-Compatible Digital Data

Conventionally, all spiral bevel gears are manufactured by machining forged gear blanks on gear cutting machines. Thus, it was decided to use the kinematics of these gear machines (generators) to develop the gear tooth geometry. Except for minor changes, most gear generators work on the same basic principle. Any deviations among the machines are considered by modifying one or more of the input machine parameters (settings). Figure 1 and Table 1 explain the algorithm used to generate the geometry of the spiral

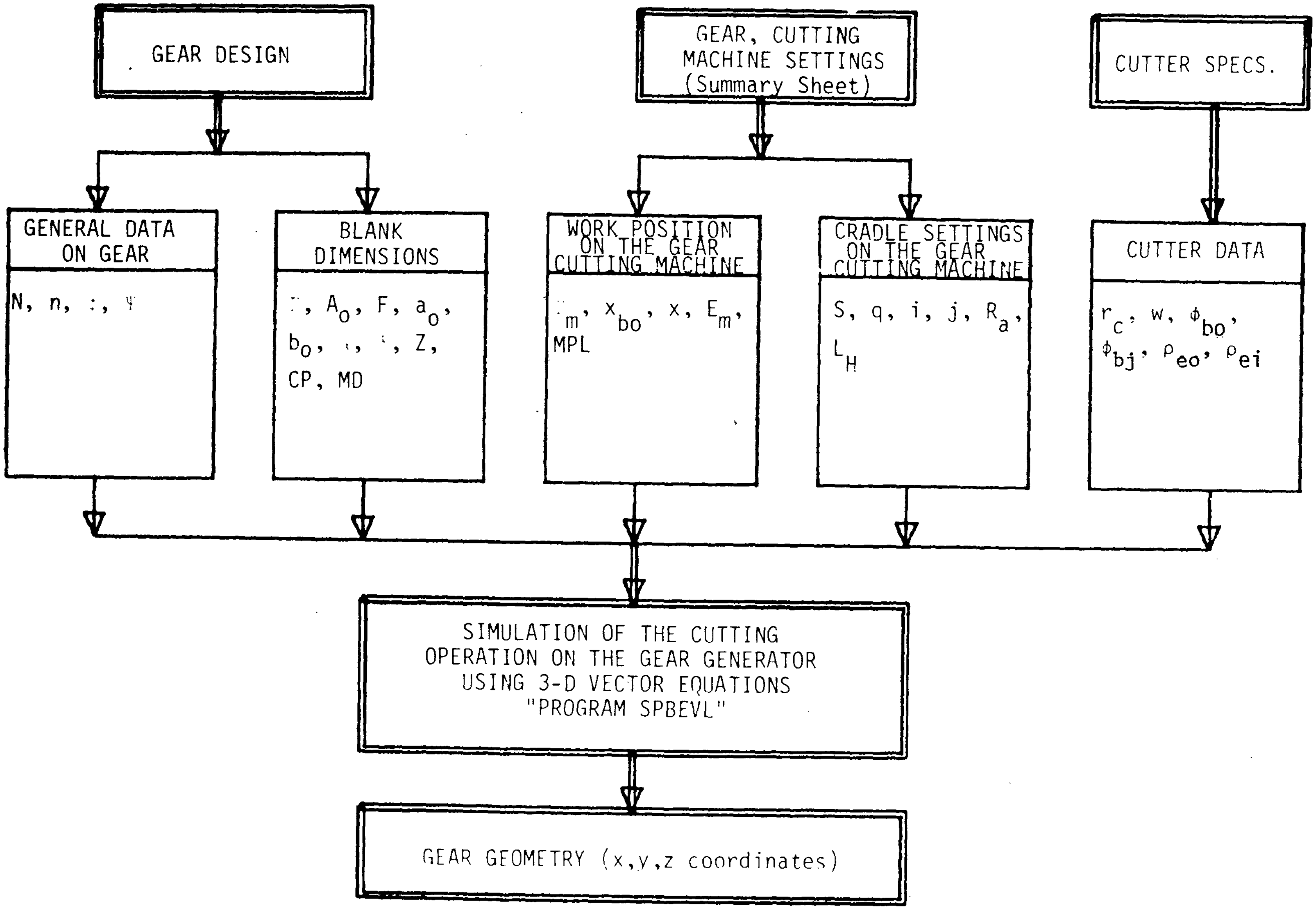


FIGURE 1. Input Data Necessary for Generating Sprial Bevel Gear Tooth Profile

(Explanation of these Data is Summarized in Table 1)

TABLE 1. Description of Input Data Given in Figure 1

General Gear Data:	N, Number of teeth on the gear; n, Number of teeth on the pinion; ϕ, Pressure angle; Ψ, Spiral angle.
Blank Dimensions:	Γ, Pitch angle; A_o, Outer cone distance; F, Face width; a_o, Addendum; b_o, Dedendum; α, Addendum angle; δ, Dedendum angle; Z, Distance between pitch apex and crossing point; CP, crossing point; MD, Mounting distance.
Work Position:	Γ_m, Root angle; x_{bo}, x, and E_m, Distances described in Reference 1. Machine Plane (MPL), Plane parallel to X-Y plane and passing through the cutter center (Figure 2).
Cradle Settings:	S, Length from cradle center (C_{cr}) to center (C_c) (Figure 3); q, Cradle position angle; i, Angle of tilt of cutter; j, Direction of tilt (Figure 4); R_a, Ratio of roll (work rotation speed/cradle rotation speed); L_H, Linear motion of the cradle along its axis.
Cutter Data:	r_c, Cutter radius; w, Cutter width; ϕ_{bo}, Angle of cutter outer surface; ϕ_{bj}, Angle of cutter inner surface; ρ_{eo}, Outer tip radius of the cutter; ρ_{ei}, Inner tip radius of the cutter.

bevel gears. As shown in Figure 1, the procedure begins at the design stage where the general gear data and the blank (workpiece) dimensions are determined. Then by using a gear cutting machine (in the U.S. most of the gear cutting machines are manufactured by the Gleason Works, Rochester, N.Y.), the workpiece is positioned according to the work position parameters and the cradle is set according to the cradle setting parameters. A straight-sided tooth cutter then "generates" (both the cutter and workpiece rotate in space) the involute (or any other) profile on the gear tooth surface.

To obtain the exact description of the spiral bevel gear tooth geometry, it is necessary to simulate the motions of a gear cutting machine used to manufacture spiral bevel gears(5). Figure 2 explains the 3-D vectors and angles involved in generating the gear tooth geometry. As seen in Figure 2, an arbitrary point, P, which lies both on the cutter face and on the gear tooth surface, is chosen. Its location with respect to the cutter axis is calculated in a vector form in terms of the cutter radius, r_c; cutter rotation angle, θ; distance of P from the cutter blade tip; cutter tilt, i (with respect to cradle axis as explained in Figure 3); the direction of tilt, j; the cradle position, g; (both lie in the machine plane as shown in Figure 4), and the cutter blade geometry. Similarly, the position of P is also calculated as a function of the workpiece geometry and its orientation. Using these two vector equations, normal and tangential velocities of P with respect to the cutter axis are calculated. So that P be an actual point on the gear tooth surface, the normal velocity to both the cutter and tooth surface at P must be zero. If not zero, the vector computations are iterated upon the cradle position, q; until the normal velocity is equal to zero, and hence a point on the tooth surface is generated. By considering that P is on both the workpiece and the cutter and by rotating the cutter, i.e., changing the rotation angle (Θ) in increments, it is possible to simulate the gear cutting process. As a result, the points on the surface of the gear tooth are generated.

Task 2. Computer Aided Design (CAD) of Forging Dies

During the forging process, both the forged gear and the dies experience dimensional variations due to elastic deflections, bulk shrinkage

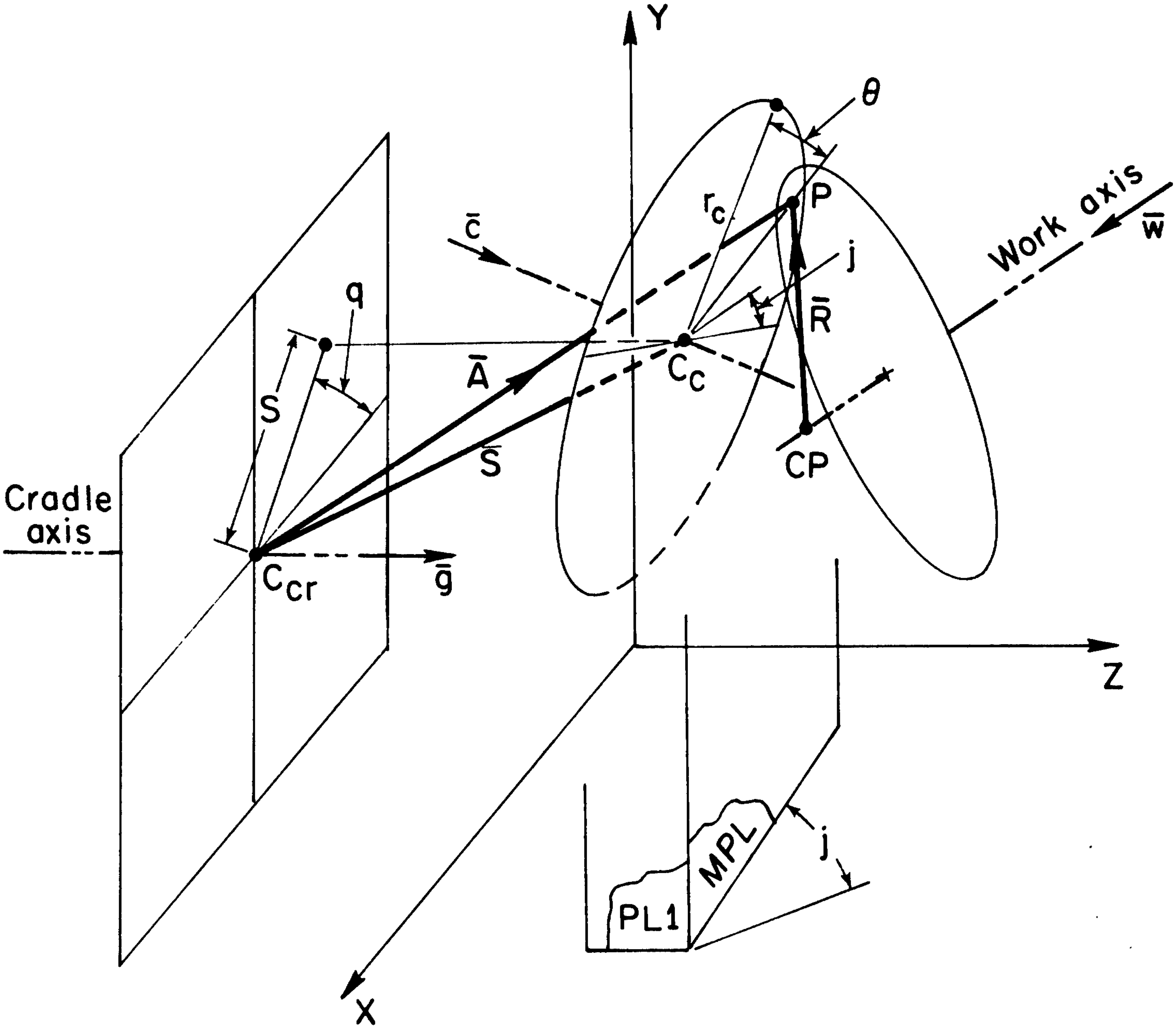


FIGURE 2. A Simplified Isometric View of Gear Generating Machine Kinematics

C_{cr} = Cradle Center; C_c = Cutter Center
CP = Crossing Point
MPL = Machine Plane; PL1 = Plane 1
S = Projection of $\bar{S}$ on X-Y Plane
P = Point on both Cutter and Workpiece Surface

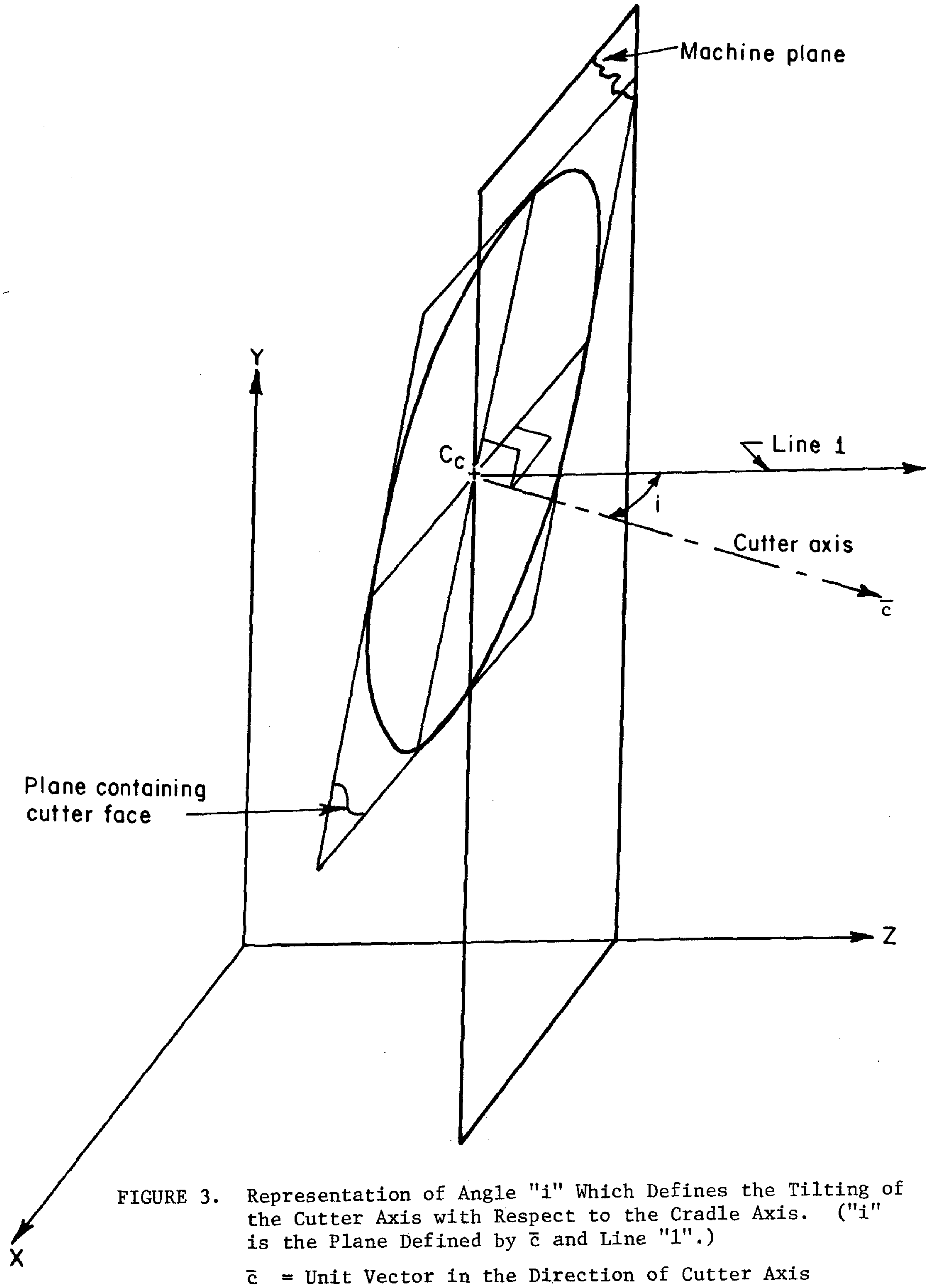


FIGURE 3. Representation of Angle "i" Which Defines the Tilting of the Cutter Axis with Respect to the Cradle Axis. ("i" is the Plane Defined by $\bar{c}$ and Line "1".)

$\bar{c}$ = Unit Vector in the Direction of Cutter Axis

C_c = Cutter Center

Line "1" = Line Perpendicular to Machine Plane

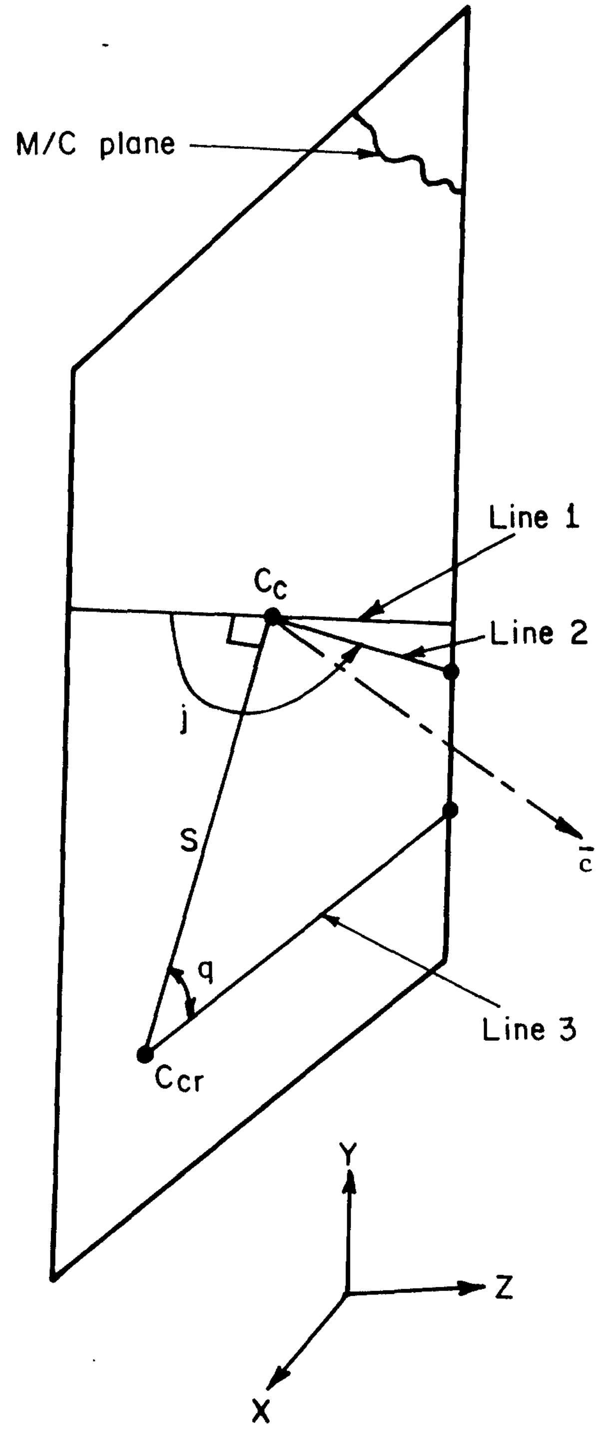


FIGURE 4. Representation of Angles "j" and "q" Which are Both in the Machine Plane

Line "1" = Reference Line on the Machine Plane; this Line is Perpendicular to Line C_cC_{cr}

C_cC_{cr} = Projection of Line Joining the Cutter Center C_c and the Cradle Center C_{cr}

$\bar{c}$ = Unit Vector in Cutter Axis Direction

Line "2" = The Projection of the Cutter Axis on the Machine Plane (i.e., Direction of Tilt)

Line "3" = Line Parallel to the Projection of the Work Axis on the Machine Plane and temperature differentials. To obtain the desirable accuracy in the forged gears, each of the geometrical variations mentioned above must be estimated and the die geometry must be corrected accordingly. For this purpose, Task 2 included several subtasks, as briefly discussed below.

Subtask 2.1. Calculation of the Stress Distribution and Forging Load. To determine the elastic deflections of the forging dies, stresses acting on the die during the forging process should be determined. Both the slab method(6) and the finite element method(7) were used to estimate the stresses acting on simplified gear tooth cross sections. An average forging pressure, p, at complete die cavity filling was estimated to be $p = 3.5\ \bar{\sigma}$, where $\bar{\sigma}$ is the flow stress of the forged material and the value of friction coefficient is $\mu = 0.35$.

Subtask 2.2. Estimation of Elastic Die Deflections Due to Mechanical Loading. Using the average forging pressure, and from the dimensions of the gear, the average stresses in the horizontal (σ_x) and the vertical (σ_y) directions were estimated. Accordingly, the elastic deformations due to these forging stresses were simply expressed as:

$$e_x = \frac{\sigma_x}{E} - \nu \frac{\sigma_y}{E} \qquad \text{(in./in.)} \quad ,$$

and

$$e_y = \frac{\sigma_y}{E} - \nu \frac{\sigma_x}{E} \qquad \text{(in./in.)} \quad ,$$

where ν is Poisson's ratio and E is the modulus of elasticity.

Subtask 2.3. Calculation of Temperature Distributions. To estimate the elastic deflections of the die and billet due to temperature differentials, it is necessary to estimate the temperature in the forged material and in the dies. For this purpose, the finite difference method(1) was used to solve the heat transfer equations. The results of an example set of temperature calculations is shown in Figure 5, in the form of isotherms. Again, to simplify the calculations, average temperatures of the die and the billet were assumed. Therefore, the corrections for the temperature changes are uniform for all points in the billet and the die. For the

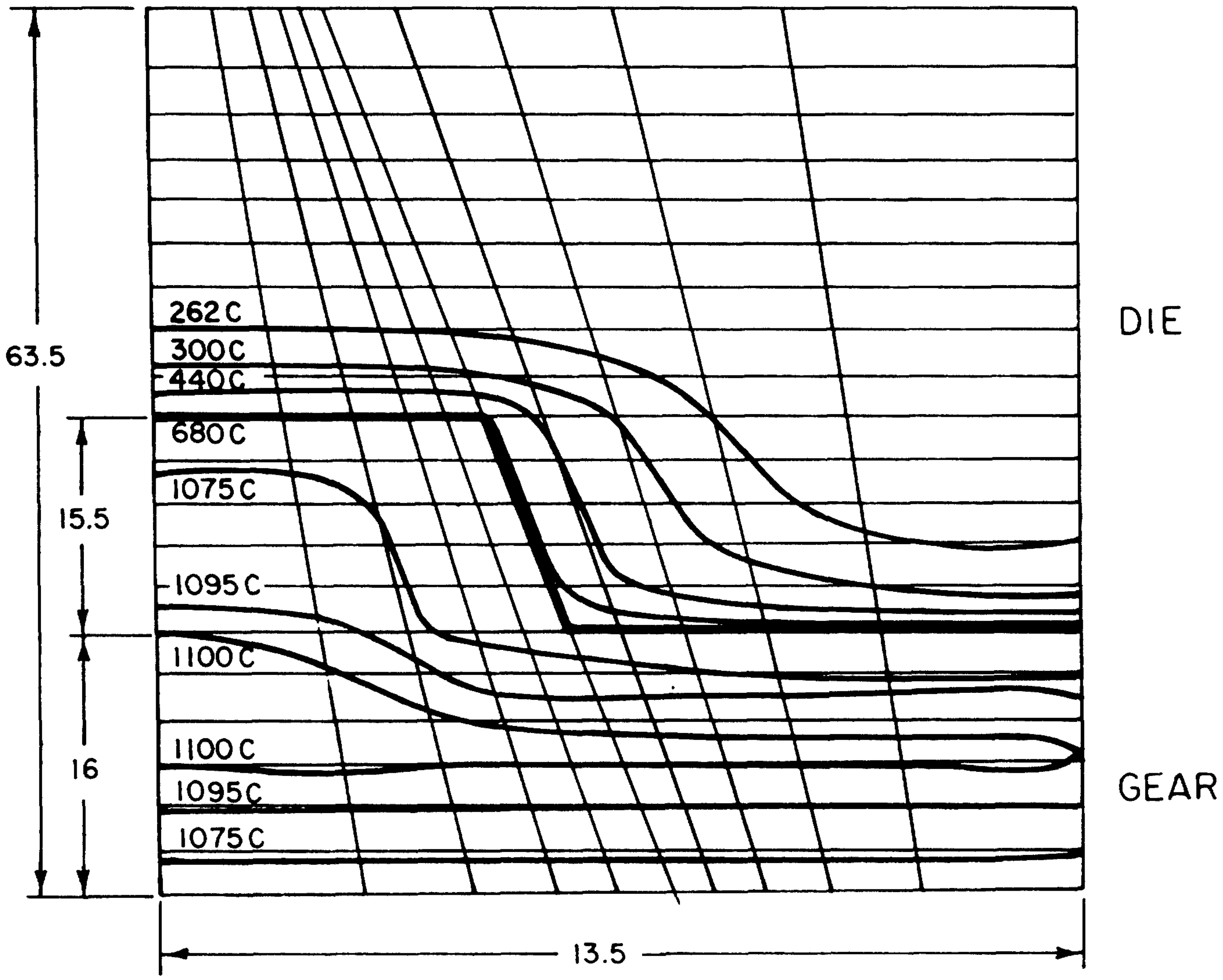


FIGURE 5. Example Temperature Distribution (Isotherms) in Gear and Die After 0.1 Second (Initial Billet Temperature = 2,012° F (1,100° C), Initial Die Temperature = 500° F (260° C)

billet, the elastic deflections can be computed from

$$e_{tb} = \alpha_b (T_b - T_\phi) \qquad \text{(in./in.)} \quad ,$$

where e_{tb} = elastic deflection due to temperature differentials,

α_b = coefficient of thermal expansion of the billet material,

T_b = average billet temperature during forging,

T_ϕ = ambient temperature.

Similarly for the die

$$e_{td} = \alpha_d (T_d - T_\phi) \quad .$$

Thus, the overall die and gear tooth elastic deflections due to temperature differentials (e_t) can be expressed as

$$e_t = e_{tb} - e_{td} \quad .$$

Subtask 2.4. Estimation of the Bulk Shrinkage Due to Shrink Fit Assembly. The change of die dimension, in the radial direction, due to shrink fitting of the die assembly has to be taken into consideration. A simple solution based on thick circular cylinders under internal pressure was used(1) to compute the elastic deflection (e_r) of the inner radius of the die assembly.

Subtask 2.5. Modification of the Gear Tooth Geometry. The results of the elastic corrections for the chosen gear geometry and process conditions were as follows:

e_t (elastic deflection due to thermal shrinkage) = 0.02 in./in.

e_y (elastic deflection in vertical direction due to forging load) = 0.002 in./in.

e_x (elastic deflection in horizontal direction due to forging load) = 0.001 in./in.

e_r (elastic deflection due to shrink fitting) = 0.001 in./in.

These results demonstrated that the largest component of the elastic deflections were due to temperatures.

Early in Phase I, it was decided that "precision" forging the spiral bevel tooth geometry to finish tolerances would be very difficult, at least in the initial stages of the study. Therefore, a machining allowance of 0.007 inch was to be provided on each flank of the gear tooth. Thus, the rough machining operation would be replaced by the close tolerance forging technique while the finish machining operation would still be conducted in the initial phase of this development program. Accordingly, the dimensions of the electrodes, used for EDMing the forging dies, were modified to include the following dimensional corrections:

- deflections due to thermal shrinkage, vertical and horizontal forging pressures and die assembly by shrink fitting
- allowance for electrode overburn and wear during the EDM process (these were based on existing experimental data)
- allowance for final machining the forged gear tooth.

It was decided that the EDM electrodes were to be machined from graphite, using a spiral bevel gear cutting machine. NC machining was considered but was found to be uneconomical. For machining the electrodes with appropriate dimensional corrections, the gear cutting machine has to be set by selecting certain parameters before performing the electrode cutting operation. To obtain the machine settings for machining the electrodes, average corrections for temperature (e_t), elastic deflections (e_x,e_y), and shrink fitting (e_r) were calculated, as described. Hence, the total correction, in the radial direction, Δr, is given by:

$$\Delta r = (e_t + e_x + e_r) \cdot r \quad ,$$

and in the Z direction (axis of gear)

$$\Delta Z = (e_t + e_y) \cdot Z \quad .$$

These corrections were applied to the machine settings, cutter and blank dimensions to obtain their new values. The new values were expressed as functions of the corrections and the old values(1), i.e.,

$$\text{new setting} = F(e_t, e_x, e_y, e_r, \text{old setting})$$

Task 3. Development of the Interactive Computer Aided Design System

The objective of this task was to consolidate all the mathematical analyses (temperature calculations, gear geometry, calculations of stresses and deflections, and determining the machine settings for cutting the electrodes), into an overall interactive graphics system of computer programs. This system was developed and called "SPBEVL". "SPBEVL" is an interactive computer program for computing x,y and z coordinates of the points describing the surface of the gear tooth. After computation, SPBEVL displays the results on an interactive graphic display terminal. Figures 6 and 7 show typical displays for a gear and a pinion. Figure 8 shows a tooth form. By rotating and enlarging the display, the user is able to check for possible errors. From this geometry, tooth cross sections are easily generated, as shown in Figure 9.

The geometry corrections mentioned before, can then be obtained by specifying the following data to program SPBEVL:

1) Forging conditions
2) Material properties
3) Die assembly specifications.

The material properties (e.g., flow stress, modulus of elasticity, the heat conduction coefficient, etc.) were obtained from the technical literature. The forging conditions (e.g., die temperature, stock temperature, lubrication, etc.) can be obtained either from the shop floor or can be selected by the designer, using past experience. Die assembly specifications are generally available at the design office. With these additional input values, the SPBEVL computer program corrects the gear tooth geometry. Using this corrected geometry, SPBEVL calculates the blank dimensions, cutter specifications, and the machine settings for cutting the electrode required for EDMing the die. The electrode geometry can also be displayed on the graphics terminal screen, if desired.

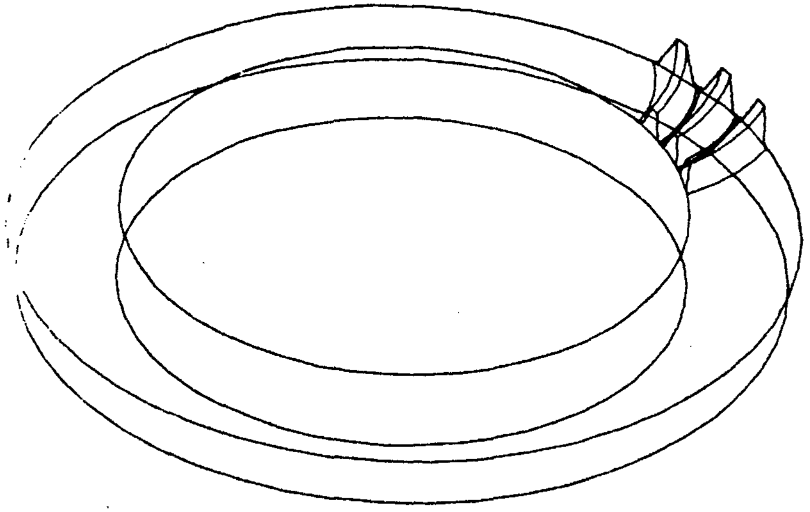


FIGURE 6. Isometric View of a Sprial Bevel Ring Gear as Displayed on the Graphic Display Terminal

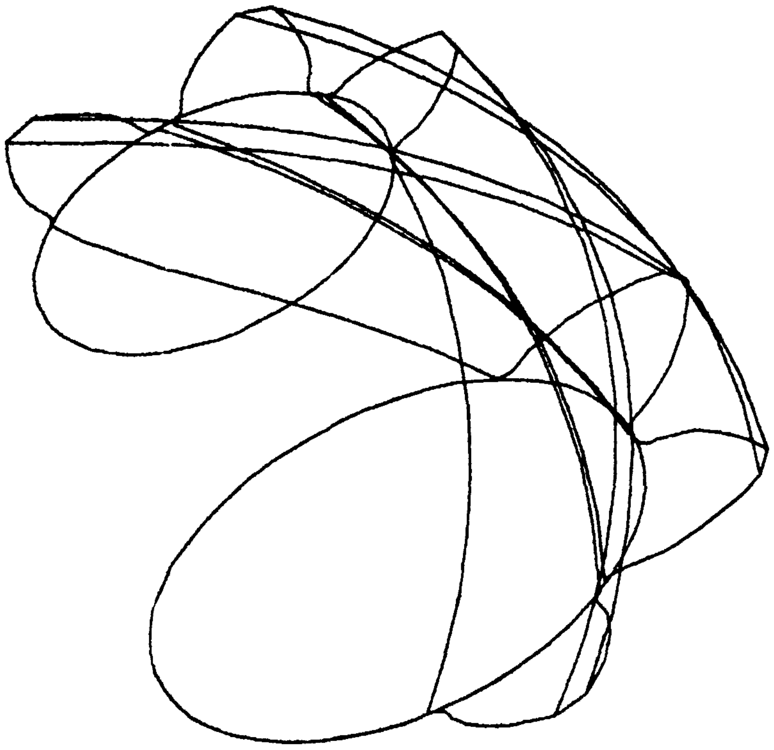


FIGURE 7. Isometric View of a Spiral Bevel Pinion as Displayed on the Graphic Display Terminal

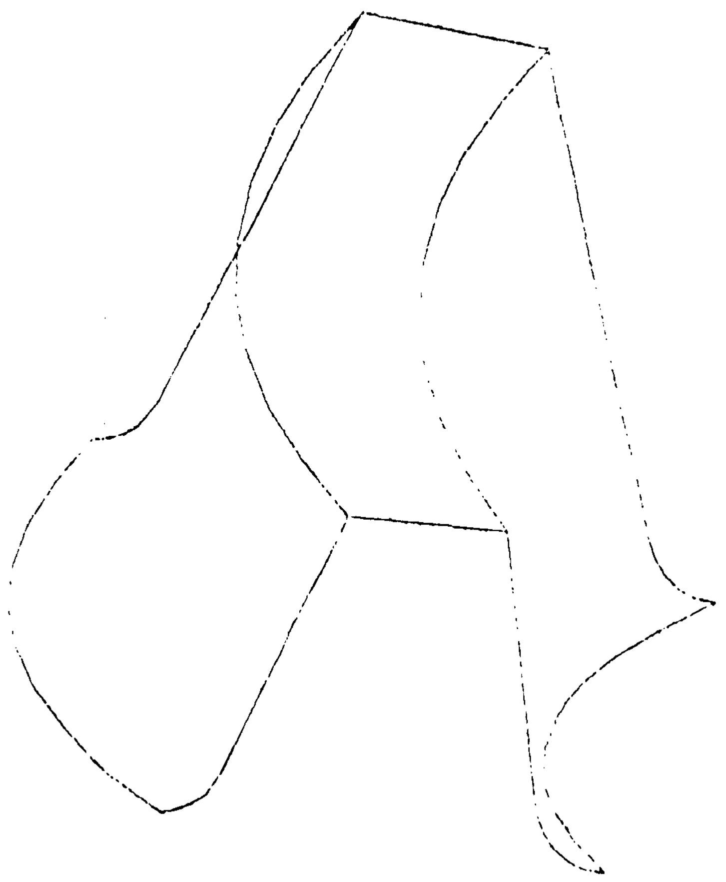


FIGURE 8. Tooth Form as Displayed on the Graphic Display Terminal

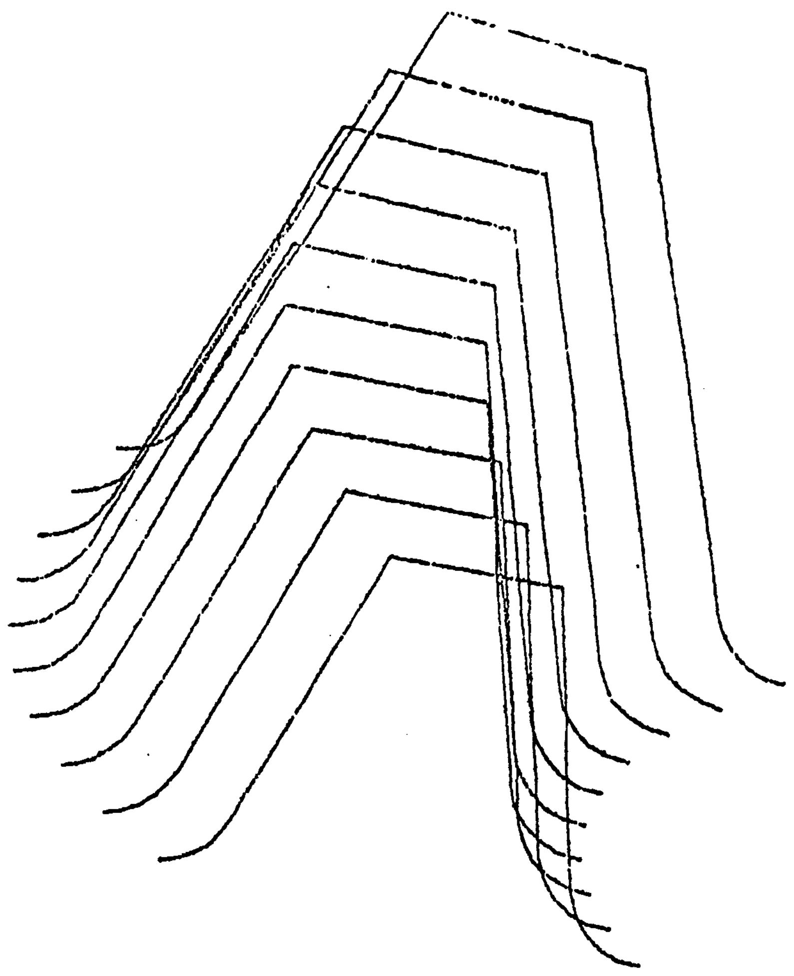


FIGURE 9. Cross Sections of a Tooth as Displayed on the Graphic Display Terminal

Discussion of the Work Conducted in Phase II

Phase II of the present project, the main topic of this report, was conducted by carrying out the following five tasks:

Task 1: Preform Design
Task 2: Tool Design
Task 3: Manufacturing of Forging Dies
Task 4: Forging Trials
Task 5: Finishing and Dimensional Checking of Forged Gears

Each Phase II task is described in the following paragraphs.

Task 1. Preform Design and Manufacture

One of the most important aspects of the forging process is the proper design of preforming (or blocking) operations. The following features were considered in the design of the preform of the spiral bevel gear considered in this project:

1. Assure Defect-Free Metal Flow and Adequate Die Filling. Adequate metal distribution is necessary in the blocker design to avoid forging defects, such as cold shuts and folds(8). The preform was designed as a solid ring (no teeth) with the outer dimensions as close as possible to the outer dimensions of the finished gear. This minimizes the amount of material to be moved during forging and this in turn, enhances die filling.

2. Minimize the Material Lost in the Flash. In steel forgings approximately half of the cost of forging consists of material costs. On the average, 30 percent of the incoming forging stock is lost in the form of flash. Thus, approximatley 15 percent of the forging costs are in the flash material of relatively little recoverable scrap value. The design of the blocker of the gear (as will be shown later) produced no flash. That was due to the facts that the volume (or weight) of the preform was slightly larger than the volume of the finish gear, and the proper material distribution throughout the preform volume was achieved.

3. Centering of Preform in Die. The preform was designed as a pancake with its center lying exactly on the center of the die. This was thought to insure even filling of the die cavity.

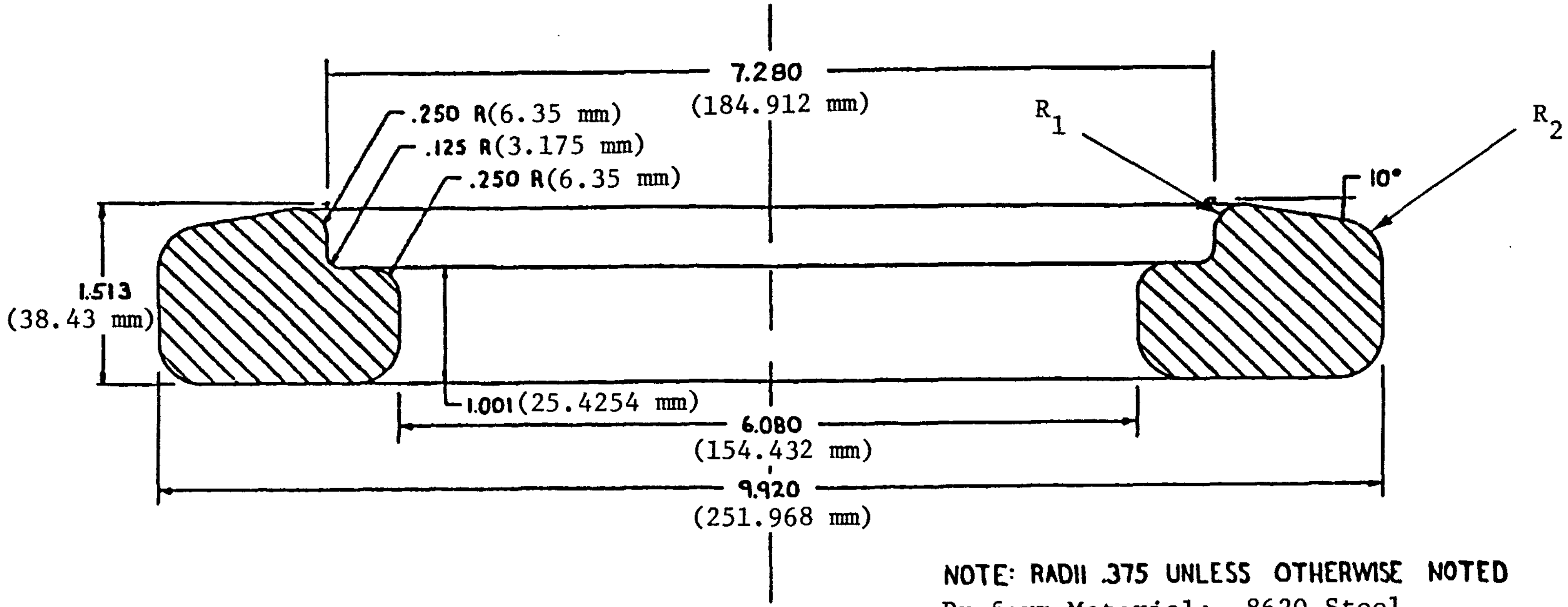
With the above considerations, an initial preform design was developed as shown in Figure 10. Figure 11 shows the preform positioned in the die. Later, another preform was designed and used in the forging trials, as discussed later. The new design shown in Figure 12 was wider so that the metal would not have to move very far to fill the cavity. The size of the corner radii was also reduced to provide more material at the corners. The billet material that was used for forging spiral bevel gears was cut from bar stock. The billet was upset to form a pancake having the proper diameter. The pancake was subsequently machined to the dimensions specified for the preforms.

Task 2. Tool Design

The forge tooling was designed by using the results of Phase I of this project. The die assembly is a two-piece design. The die insert, with the teeth, is one piece with a die ring around the insert to form the outer diameter of the forging. At the center of the die is the die insert and the center kickout. The insert forms the inner diameter of the forging while the kickout removes the gear from the die after forging. The kickout is designed to lift the part by pushing on the center flange of the gear. It is activiated by a mechanical kickout mechanism of the forge press which raises during the upstroke of the press. The kickout is also designed to contact the preform in such a way to minimize the amount of material that is moved across the face of the insert. Figure 11 shows the kickout system.

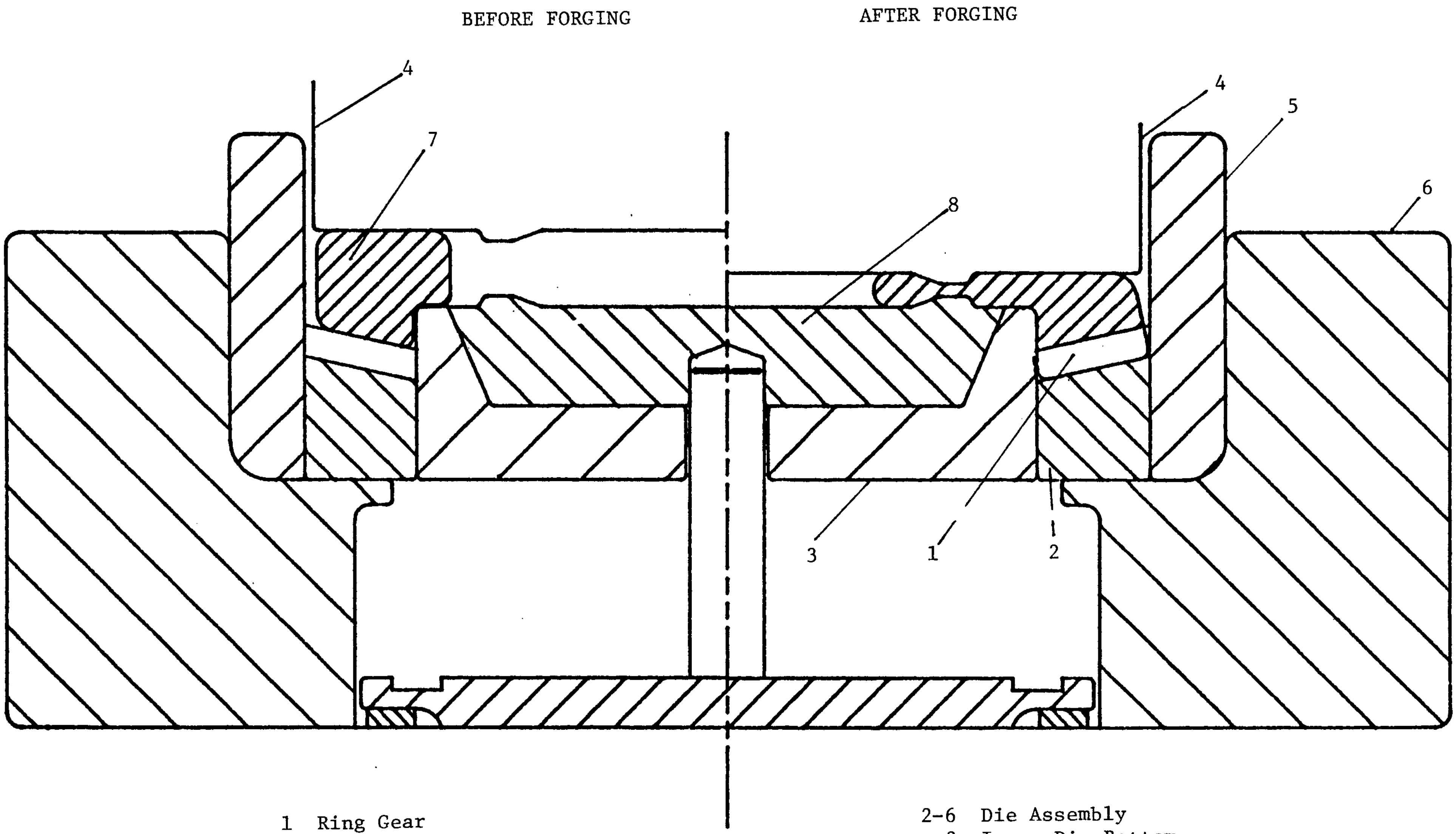
The tooling assembly is shown in Figure 13 . Incorporated in the forging design is the straight sided outer diameter with the provision of flashing toward the inner diameter. The inner diameter allows a 3/8 inch flash thickness on each side to trap the material. Inside the flash land is a gutter for excessive material to flow.

The punch-holder design is different from the die holder in that it has a solid punch without any kickout. The punch also has provisions for



NOTE: RADII .375 UNLESS OTHERWISE NOTED
Preform Material: 8620 Steel

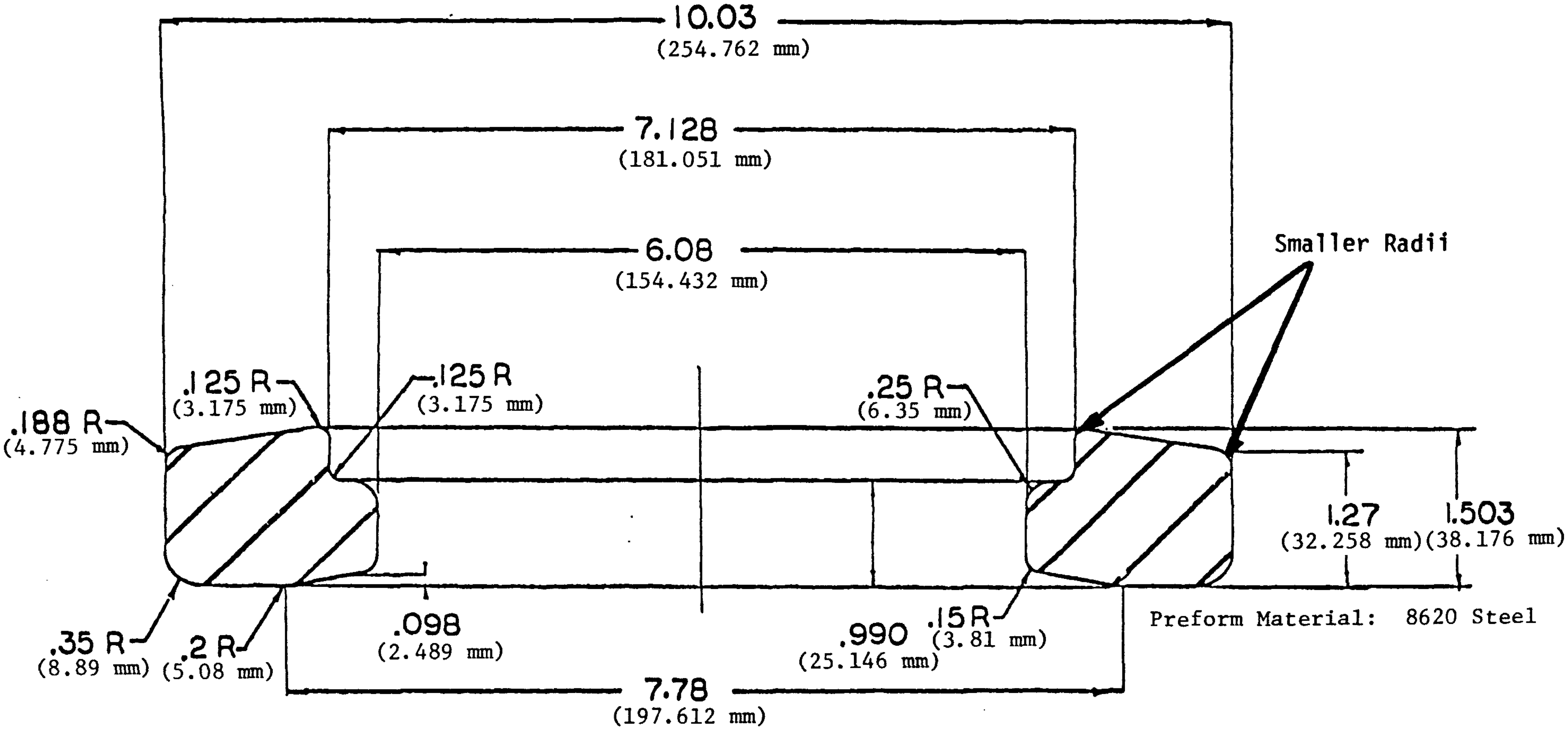
FIGURE 10. Preform Geometry for the First Series of Trials



1 Ring Gear
2 Die Bottom (With Teeth)
4 Punch
6 Die Holder
8 Kick Out Ring

2-6 Die Assembly
3 Inner Die Bottom
5 Die Ring
7 Preform

FIGURE 11. Schematic of Forging Tooling
(Dimensions of Preform are given in Figure 10)



Preform Material: 8620 Steel

FIGURE 12. Preform Design Used in Net Forging Trials

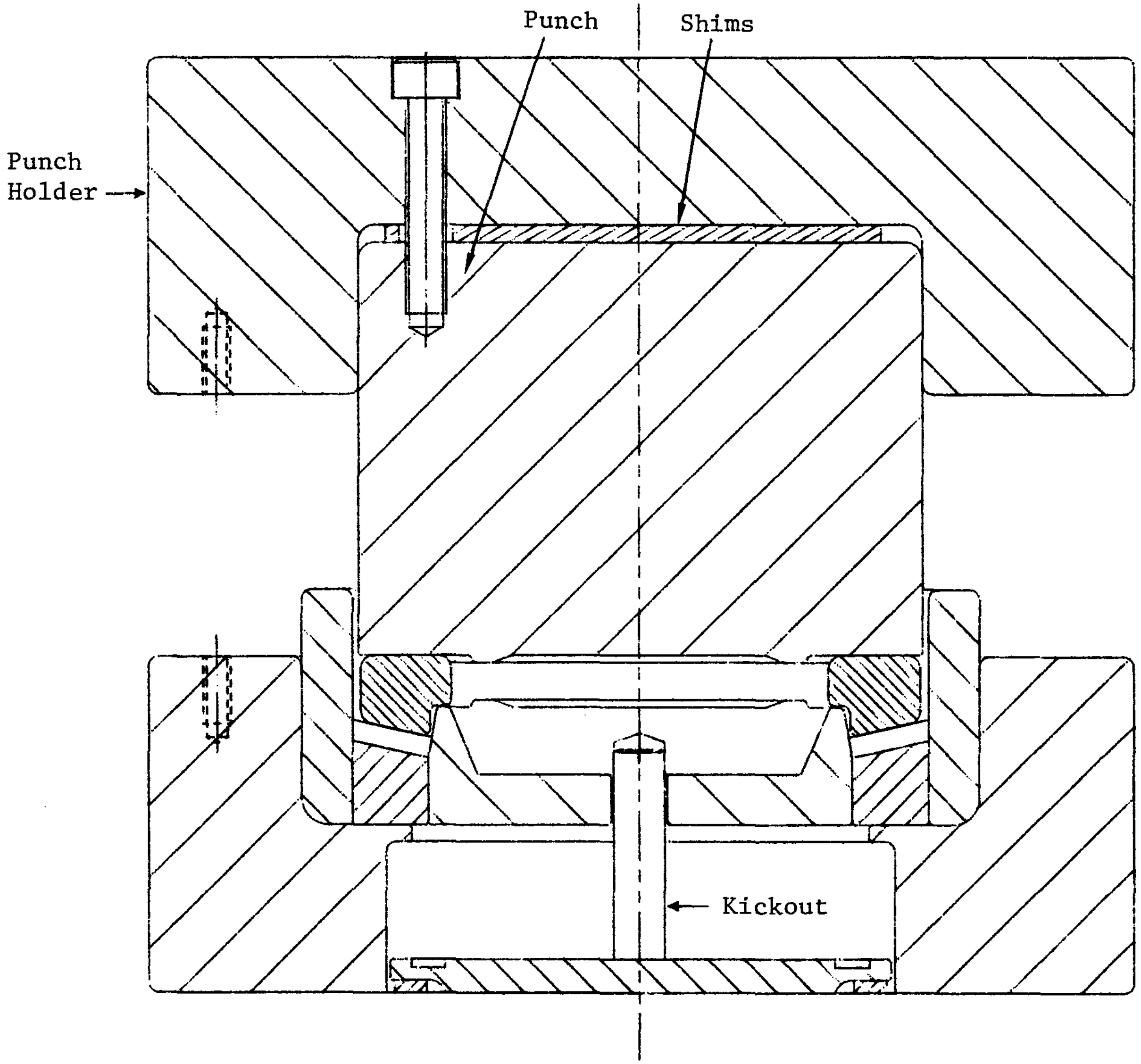


FIGURE 13. Schematic of the Forging Tooling

placing spacers or shims between the punch and punch holder to vary the forging and flash thickness. This is necessary because it was decided to conduct the forging trials on a press which has a fixed bolster with no wedge adjustment. The shims help to adjust the forging thickness and the die fill within certain limits. The components of the die tooling set-up are shown in Figure 13. The assembled tooling is shown in Figures 14 and 15.

Task 3. Manufacture of Forging Dies

Precision manufacturing of forging dies plays an important role in the success of precision forging spiral bevel gears. The use of sound die manufacturing methods is essential if the required gear precision is to be achieved.

Based on the results of Phase I of this project,(1) it was decided to use the hot work steel H-11 as a die material for the near net gear forging trials, and the hot work steel H-13 as a die material for the net gear forging trials. The billet material used in both trials was 8620 steel. The die blanks were heat treated and then machined prior to the EDM of tooth cavities. The EDM electrodes were machined on a conventional gear cutting machine, using machine settings supplied by the CAD Computer Program SPBEVL of Phase I.(1)

The electrode geometry accommodated all the corrections (elastic deflection due to loading, temperature differentials, and bulk shrinkage), as described earlier. The gear impression on the die was obtained by EDM. The EDM operation was performed using six electrodes in sequence. Each subsequent electrode was burned deeper until the required depth was obtained. Appendix "A" of this report describes the important steps in the manufacture of the forging dies (preparation of the electrode, EDM burning of the die, and the final grinding of the die after EDM).

It is worth mentioning here, that this Task (Manufacture of Forging Dies), makes use of all the data supplied from the Phase I part of this project, and hence the integration of the Computer Aided Design (CAD) with the Computer Aided Manufacturing (CAM) was achieved in the production of forged spiral bevel gears.

FIGURE 14. Assembled Lower Die Holder

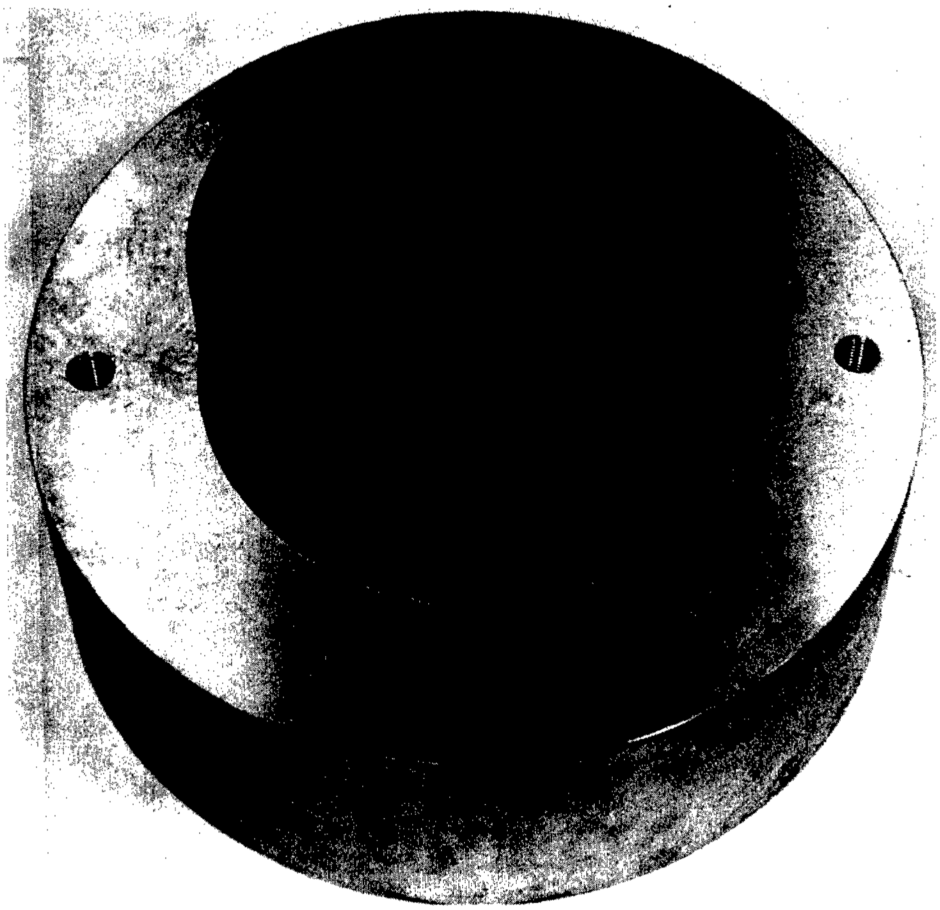


FIGURE 15. Assembled Upper Die Holder

Task 4. Forging Trials

After manufacturing the dies with the required precision as described earlier, the gear forging trials were conducted at Eaton Croproation's Forging Division in Marion, Ohio. A 3,000-ton mechanical forging press, manufactured by National Machinery Company, Tiffin, Ohio, was used to perform the trials. The press was selected based upon the anticipated forging load of about 2,500 tons(1) (2.268 x 10^6 kg) and the space available for the tooling. The ring-shaped preforms, shown in Figures 10 and 12 were machined from a forged pancake for the present experimental purposes. In actual production, they would be forged from round or round square billet with internal flash.

The preforms were heated in an induction coil that was specially designed for this program. The coil was adapted to the existing induction power supply and electrically balanced using a heat station purchased from Tocco, Inc. The 2,000° F (1,093° C) forging temperature was achieved in about 3-1/2 minutes by alternately turning on and off the power. The heat input was largely concentrated on the outer portion of the ring preform and the power was turned off to allow conduction of the heat to the inner part of the ring. The temperature was monitored, during heating, through a sight hole in the enclosed coil. An Ircon infrared temperature measuring instrument (Model R) was used to monitor the forging temperature during the trials. Provision was also made to introduce a protective atmosphere during heating via an access hole on the top of the enclosed coil.

The forging loads were monitored using load transducers attached to the frame of the press. These strain-gage devices sense the strain in the frame of the press during forging and output an electrical signal that is proportional to the load. Once the transducer system has been calibrated, the electrical signal can be read directly as load on the digital read-out device. The system used was a Model LG-II designed and built by Helms Instrument Company.

The die lubrication, used during the forging trials, consisted primarily of a water base, graphite material sprayed with pressurized air. A hand wand was used to direct the lubricant onto the die. Several billets were coated with a graphite-based coating material to reduce oxidation during heating and improve lubrication during forging. However, no advantage was noted in surface finish, die fill, or forging load. The practice was discontinued after the initially coated billets were used.

After forging, the gears were placed teeth down, in a sand-graphite mixture to reduce oxidation of the teeth during cooling. The back surfaces of the gears were still exposed to air so that the cooling rate would not be excessively slow.

Results of the Forging Trials

Three series of forging trials were conducted. During the first trials, the technological aspects of the forging procedure such as heating, lubrication, billet temperature and cooling were established. During the second forging trials, 20 gears were forged with a 0.007 inch (0.178 mm) machining allowance on both tooth surfaces. These near-net forged gears were subsequently finish machined with a single machining operation. The third series of trials were conducted to forge 20 gears with net teeth dimensions. Following, is a summary of the results of the three forging trials.

A. First Series of Forging Trials

During these trials, a gas furnace was used to heat the preforms. This resulted in excessive scale formation and poor surface finish of the forged gear teeth. The heating was done by induction in the subsequent trials. The outside diameter of the preforms was considerably smaller than the internal diameter of the die cavity. As a result, some preforms could not be centered accurately and the forged teeth configurations were not uniform.

B. Second Series: Near-Net Forging Trials

This set of trials was considered very successful for the following reasons:

1. The forged gear was uniform. All teeth looked almost alike.

This meant that the centering problem encountered during the first forging trials was eliminated.

2. The surface quality of the forged gear teeth was excellent. The induction heating of the preforms produced forgings with minimal scale. That meant that the scale problems encountered during the first forging trials, where a gas furnace was used to heat the billets, were eliminated.

Two problems were encountered during the second series of forging trials:

1. There was incomplete filling at the toe and heel of the tooth (see Figure 16). This problem was mainly due to the preform design. A cross section of the preform is also shown in Figure 10. As indicated in Figure 10, the radii R_1 and R_2 at the outer and inner part of the ring are generous. Consequently, there was not enough material at these parts to completely fill the die cavity. This is schematically indicated in Figure 17.
2. Non-uniform temperature of the billet was noticed due to the change in colors in the inner part of the ring (cooler) and the outer part of the ring (hotter, i.e., the red color was brighter). This problem could be solved later by trying different heating cycles and times and lower induction frequency to obtain a uniform preform temperature.

C. Third Series: Net Forging Trials

The net forging trials were successful in producing gears with excellent surface quality and with superior die fill, as compared to near-net forging trials. The new preform design used in this trial was the main reason for the better fill in the toe and heel of the gear. As shown in Figure 12, the preform has a smaller radii in the toe and heel of the gear, as compared with the near-net preform. This additional material in the toe and

FIGURE 16. Incomplete Filling at the Toe and Heel of the Tooth Due to Inaccurate Preform Design

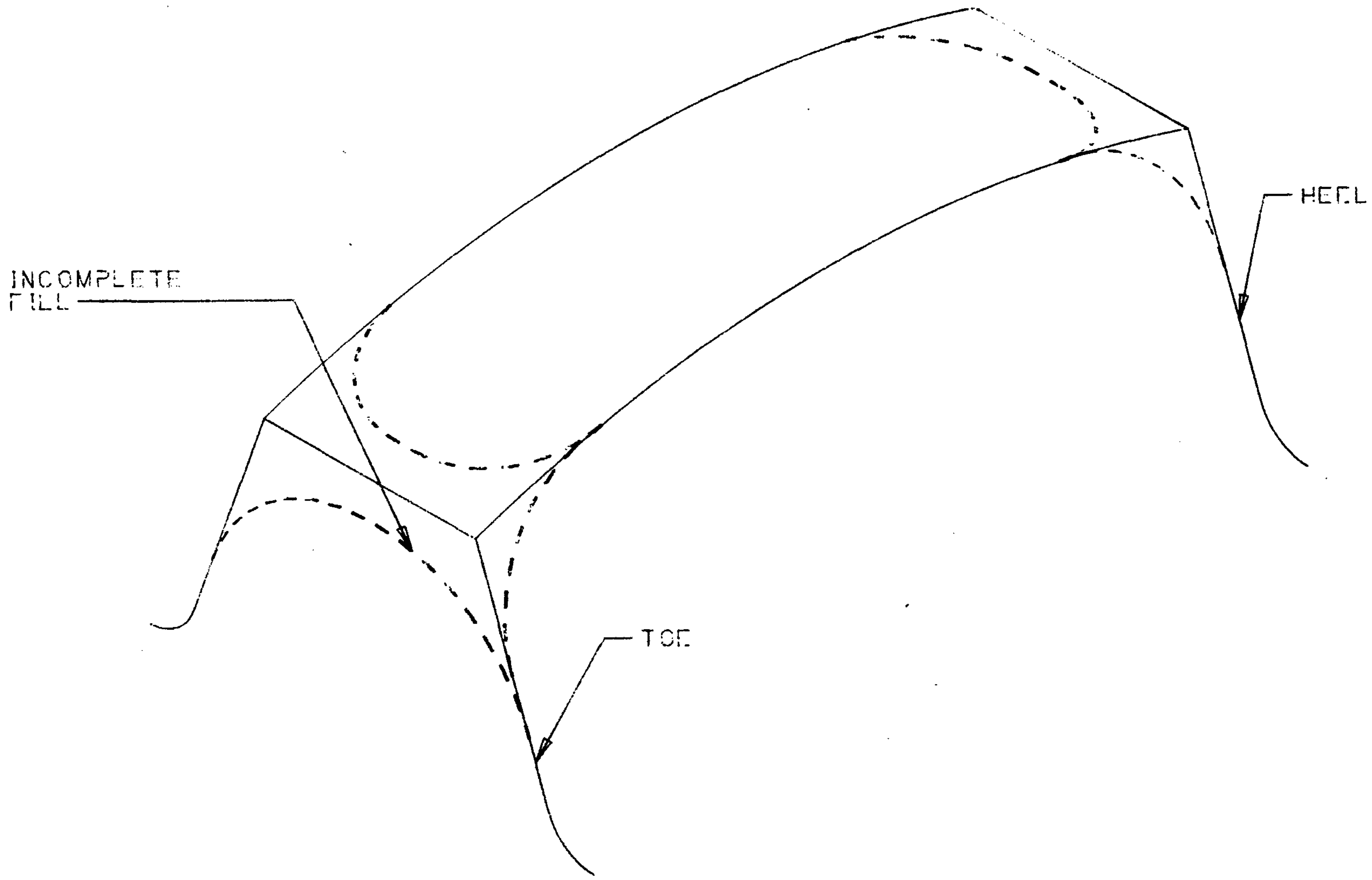


FIGURE 17. Schematic Representation of the Incomplete Filling of the Toe and Heel of the Forged Gear From the Second Forging Trials

heel enhanced the filling of those parts. Figure 18 shows a picture of the net forged gear after it was cleaned.

The results of the near-net and net forging trials are described in detail in Appendix B.

Task 5. Finishing and Dimensional Checking of Forged Gears

A. Near-Net Forged Gears

To prepare the near-net forged gears for finish machining of the tooth form, all surfaces (except the teeth) were machined. The back surface and the bore are reference surfaces for locating the gear during tooth finish machining. It is important that these surfaces be in the proper orientation with respect to the forged gear teeth. To insure this, these surfaces were cut with the gear teeth resting in a nest, designed specifically for locating the forged gear on the pitch line of gear teeth, as shown in Figure 19. After machining the reference surfaces, the gears were placed on a conventional gear cutting machine and finish cuts were performed on the gear tooth surfaces. The machining stock on the flanks of the teeth was found to be 0.012 inches (.3048 mm), rather than the designed 0.007 inches (0.178 mm). However, all of the teeth cleaned up on both the coast and drive sides of the gears and the contact pattern (obtained by rolling the forged and finish-machined gear with the matching machined pinion) very much resembled that obtained on the master gear set (matched gear and pinion set).

B. Net Forged Gears

The same nest design, shown in Figure 19, was used to machine the back face and the bore of the net forged gear. After cleaning, the forged gears were rolled with the cut pinions. Again, the contact pattern was excellent.

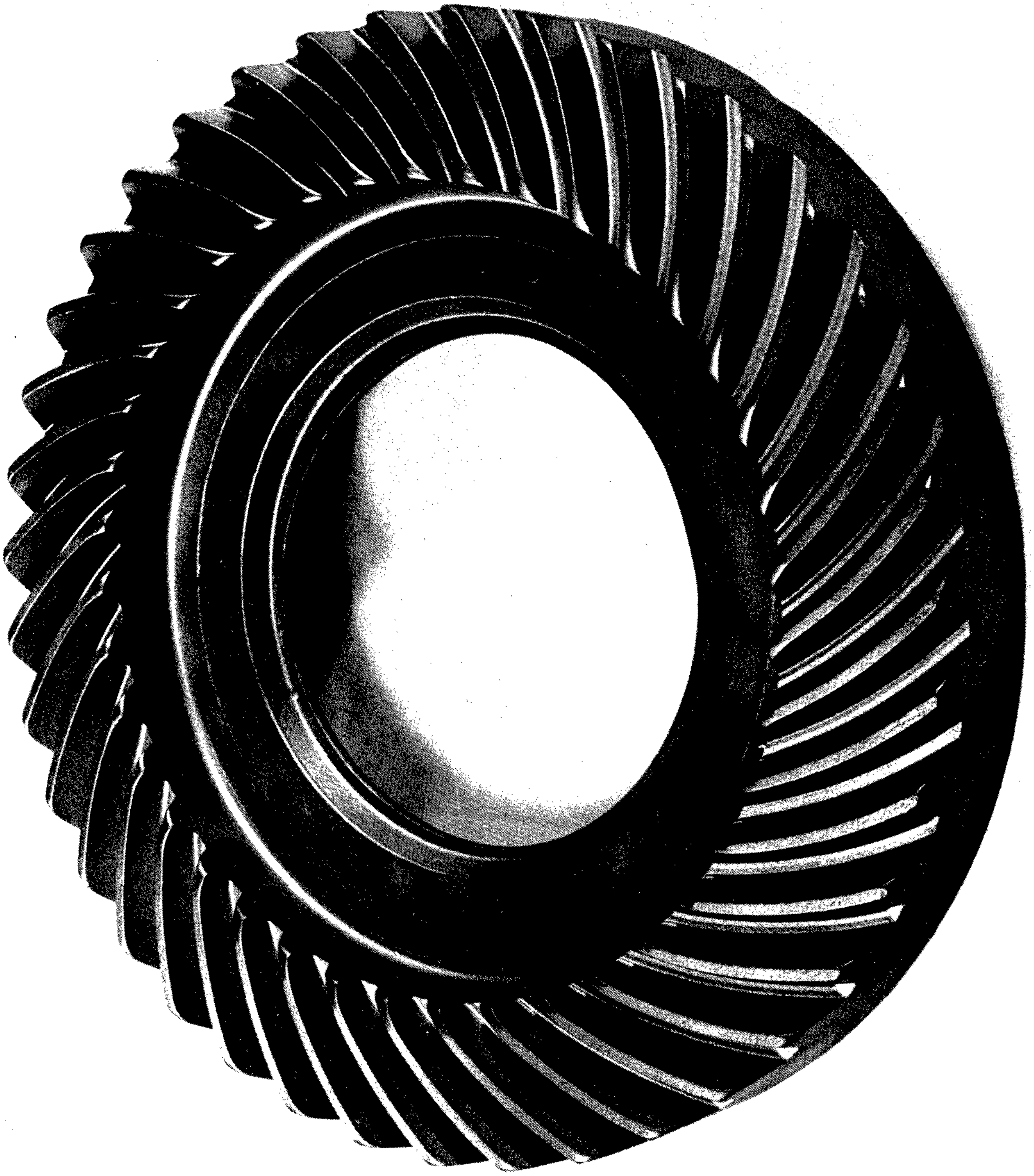


FIGURE 18. A Cleaned Net Forged Gear

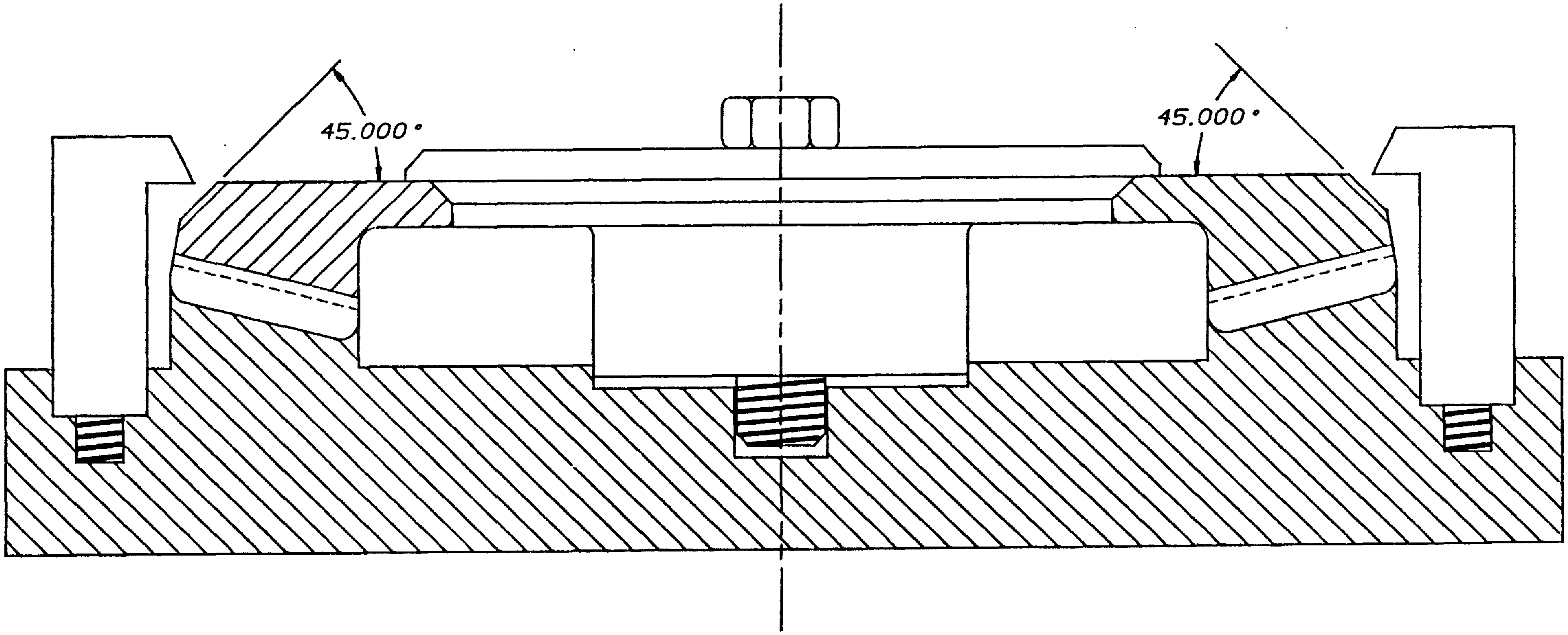


FIGURE 19. Clamping Arrangement of the Nest, used for Machining the Back Side of Forged Gears

Dimensional Checking of Forged Gears

The forged gears were checked for dimensional accuracy on the Zeiss machine. The Zeiss machine is a computer controlled coordinate measuring machine (manufactured by Zeiss Corporation in West Germany) which produces plots of the tooth form variation as compared to the tooth surface of the cut master gear, produced by conventional cutting on a Gleason generator.

Figure 20 shows one of the forged gears while being measured on the Zeiss machine. The plots, shown in Figure 21, show the relative deviation of the forged tooth profile as compared to a "master gear" tooth produced by conventional cutting (using a Gleason generator). Note that the relative error at the center of the profile is zero, i.e., the variations were measured relative to the center of the coast and drive surface of the master gear. The scale of the relative error is shown at the left side of Figure 21. The maximum variation was 0.003 inches (0.0762 mm). This difference can be easily compensated for in the cutting of the matching pinion. Appendix C contains the details of the finishing and dimensional checking of the forged gears.

CONCLUSIONS

The main goal of this program is to demonstrate that the close-tolerance forging process, combined with CAD/CAM, is an attractive and economical method for manufacturing spiral bevel gears. To achieve this goal, the use of advanced CAD/CAM techniques to design and manufacture the forging dies is necessary. In applying the CAD/CAM techniques to sprial bevel gear forging, the following was achieved:

- In Phase I of this project, the gear geometry was generated based on the kinematics of spiral bevel gear cutting machines. This was necessary since these gear cutting machines are used to cut the electrodes used to EDM the dies. Dimensional variations of the forging

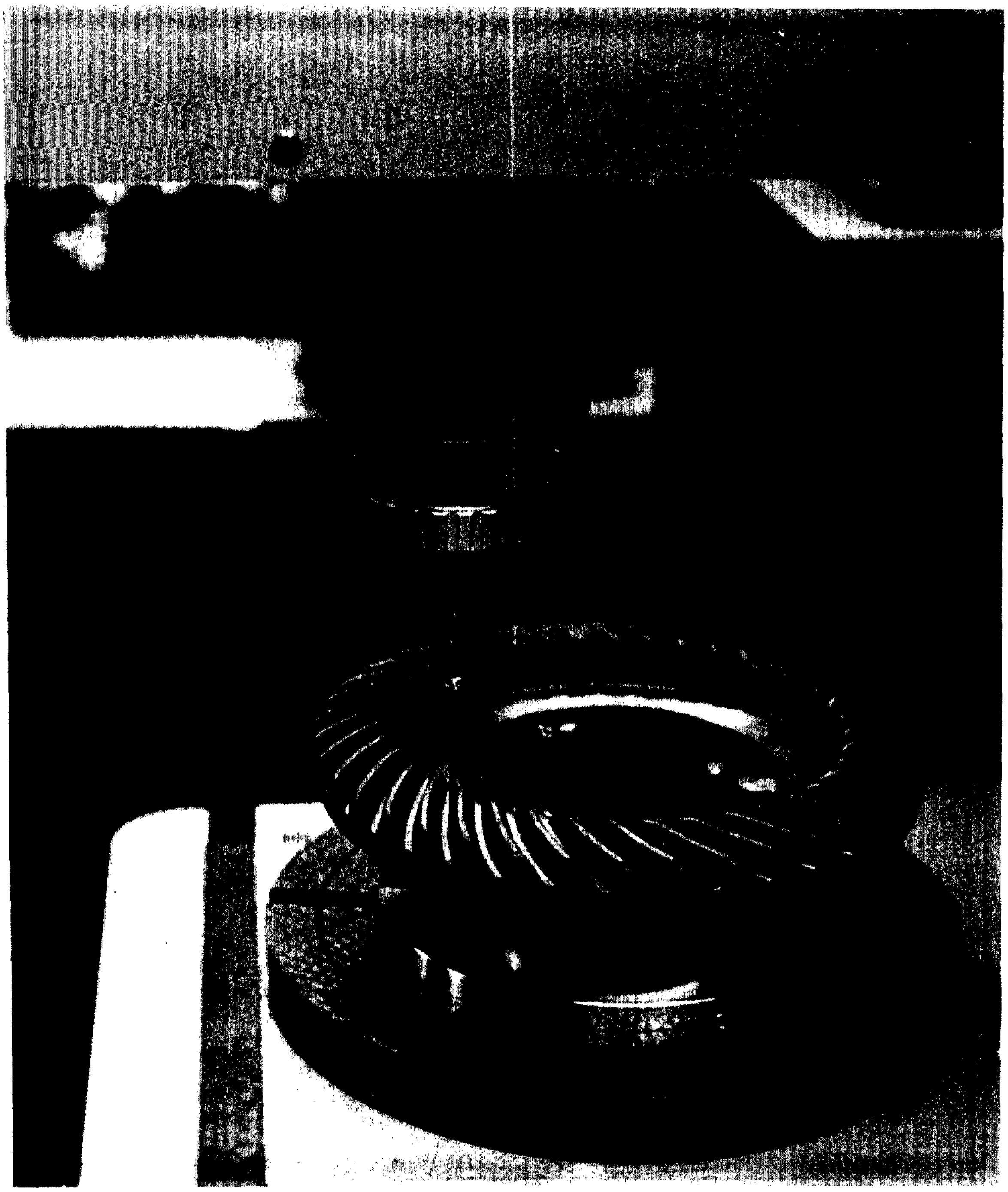


FIGURE 20. Measuring Forged Gear Tooth Form on Zeiss Machine

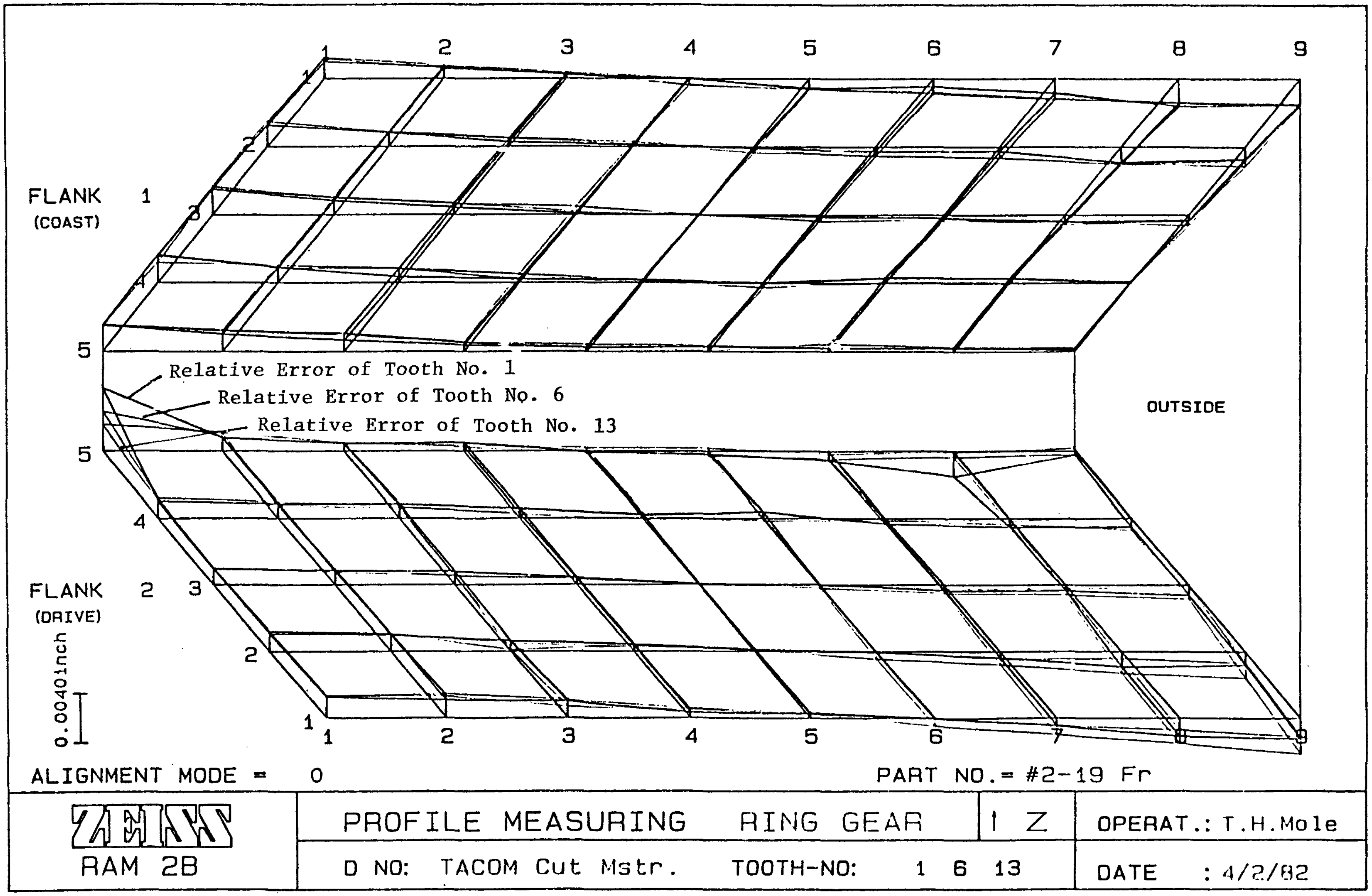
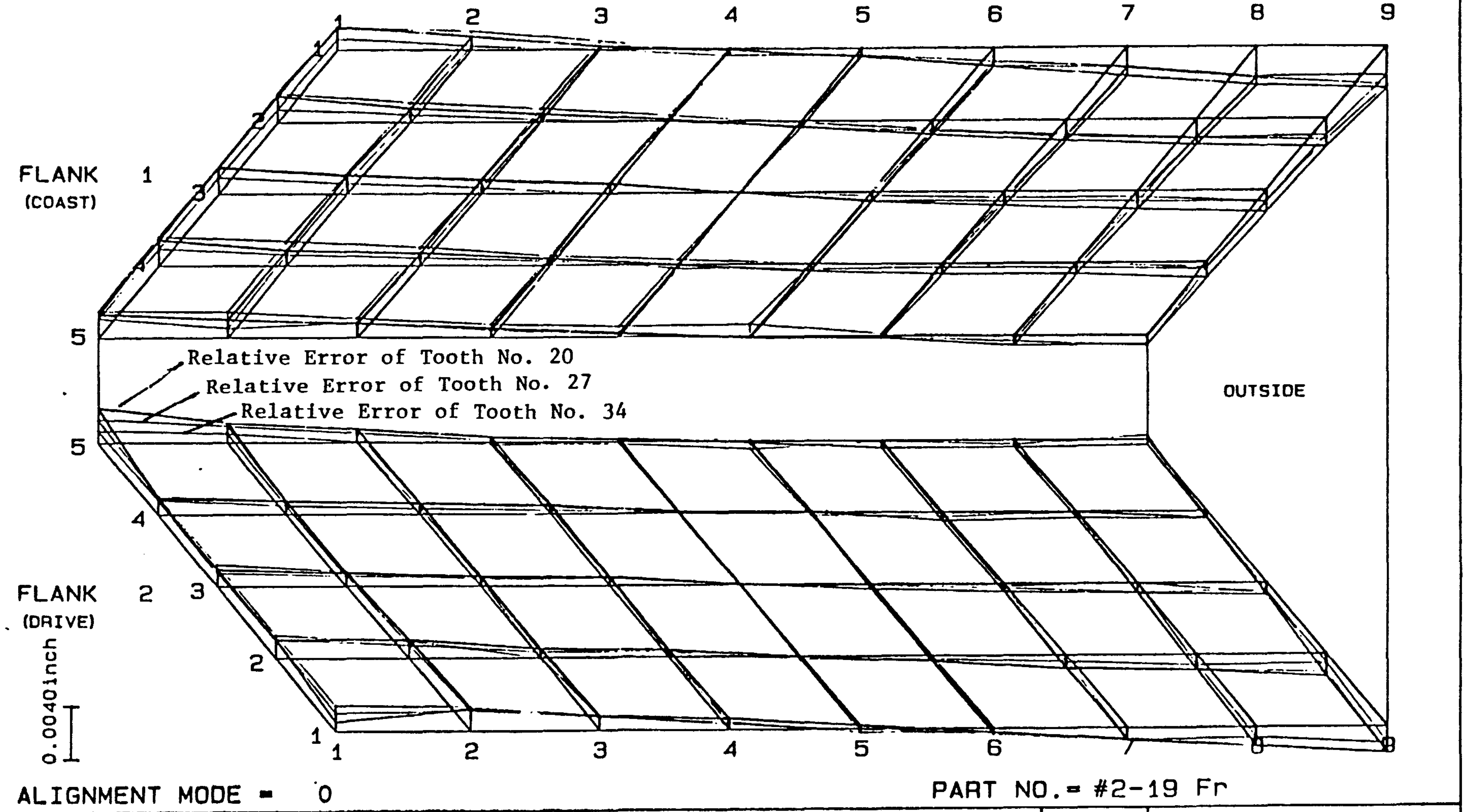


FIGURE 21. Zeiss Gear Tooth Plots, Graphically Illustrating the Tooth Form Variation of Forged Gears Versus the Cut Master Gear



ZEISS	PROFILE MEASURING RING GEAR	↑ Z	OPERAT.: T.H.Mole
RAM 2B	D NO: TACOM Cut Mstr. TOOTH-NO: 20 27 34		DATE : 4/2/82

FIGURE 21. (Continued)

dies, due to thermal shrinkage and elastic deformation resulting from thermal and mechanical loading, were also calculated and integrated into the general computer program SPBEVL. The output of the SPBEVL program is the new machine settings to be used to cut the electrodes necessary for EDMing the forging dies. The machine settings, calculated by SPBEVL, take into account all the previously mentioned corrections.

- In Phase II, the main topic of this report, the forging dies were designed and manufactured based on the results of Phase I. Thus, the integration and the application of the CAD/CAM process was achieved and demonstrated. Three sets of forging trials were conducted to close-tolerance forge spiral bevel gears. The first forging trials showed that uniform and scale-free heating was necessary to obtain acceptable surface quality of the forged gear teeth. During the second forging trials, induction heating, under a gas atmosphere (instead of a gas furnace used in the first forging trials), was used for heating the preforms. Appropriate billet coatings and die lubricants were also selected. The results of the second forging trials indicated that close-tolerance forging of spiral bevel gears, requiring only a single machining (finishing) operation is feasible and can be implemented in production. This would replace two machining operations, roughing and finishing, used in conventional manufacture of gears. The third forging trials were aimed at producing gears with net teeth dimensions. A computer controlled coordinate measuring machine was used to evaluate the dimensional accuracy of the forged gears. The measurement results indicated excellent agreement between the geometry of the forged gears and the corresponding machined gears, manufactured conventionally.

The results of this project indicate that the use of CAD/CAM in close-tolerance forging of spiral bevel gears is a practical technique and would reduce manufacturing costs. The mechanical properties (fatigue life and load carrying capability) of the forged gears were not evaluated in this project since this was beyond the project scope. However, based on data obtained on other forged bevel and spiral bevel gears, it is expected that forged gears will exhibit better mechanical properties than machined gears.

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APPENDIX A

MANUFACTURE OF FORGING DIES

APPENDIX A

MANUFACTURE OF FORGING DIES

Precision forging of spiral bevel gears is dependent on the precision with which the dies are manufactured. The use of sound die manufacturing methods is essential if the required precision is to be achieved. This Appendix describes the important aspects of manufacturing the forging dies (e.g., preparation of the electrode; EDMing of the die, and final finishing of the die after EDM).

Preparation of the Die Blanks

From Phase I, the pressure required to forge the gear was calculated to be 90,000 psi (620.5 MPa). It was also determined that the die surface temperature would be about 1,292° F (700° C). This is shown graphically in Figure 5. Using this information, a survey has been conducted to select a die material which: 1. exhibits a high impact strength, 2. maintains its metallurgical properties, specifically hot hardness at the elevated temperature operating conditions. In addition, factors such as machinability, availability and price were considered. The material selected for the near-net tooth forging trial was hot work tool steel H-11.(1) The hardness desired for maximum performance was R_c50-54. To obtain this hardness, the die was heated to 1,800° F (982° C) in an atmosphere-controlled furnace and then air cooled. The die was then tempered by heating to 1,050° F (565° C) for 3 hours and then air cooled. This was repeated to obtain a hardness of R_c52.

In selecting a die material for the net teeth forging trials, it was considered desirable to find a material with the same characteristics as that used for near-net forging, except for higher hot hardness than that of H-11 without sacrificing impact strength. The material selected was hot work tool steel H-13.(1) The hardness again was to be in the R_c50-54 range. This hardness was obtained by hardening at 1,800° F (982° C) with two temperings at 1,000° F (538° C) followed by air cooling.

The die blanks were prepared by sawing the blank from bar stock. The blanks were turned prior to heat treatment. To prepare the heat treated die for EDM, the bottom of the die was ground. This was necessary to have a qualified surface before EDM and also to remove any distortion caused by heat treatment.

EDM of Forging Dies

The corrections required for the die dimensions due to temperature differences, forging stresses, and shrinkage resulting from shrink fitting, have been discussed earlier. The dimensions of the electrode used for EDM of the die should be the same as of the new corrected die geometry. In the present project, it was decided to use a gear cutting machine (not an N/C machine) to manufacture the electrodes for the following reasons:

1. For average corrections assumed in our approach, it will be possible to machine the electrodes on gear cutting machines.
2. Companies currently machining spiral bevel gears will likely prefer to make use of their existing machinery for making the electrodes, should they decide to produce spiral bevel gears by forging.

The EDM Process

The EDM process is well known.(2) Nevertheless, a brief background on this process is helpful. In EDM, the electrode and the workpiece (die blank) are submerged in an electrically nonconductive fluid. The electrode is brought within a few thousandths of an inch to the work, and a voltage potential is applied across the electrode and workpiece. When the voltage builds up to a high enough level, it will ionize the fluid and cause an arc to pass through the fluid across the gap. If the voltage is resumed and maintained, many such arcs will form, each seeking its path of least resistance. The high temperature of the arcs and their force will melt and separate small particles from both the electrode and workpiece, and the fluid will solidify these particles and wash them away. As the particles wash away, the space will become larger, to a point where the voltage cannot jump the gap. The electrode is then advanced to decrease the gap size, and the EDM continues. The rate of metal removal is primarily dependent on power. For a given voltage, the higher the current-carrying capability of the equipment, the faster the metal removal rate. The surface finish of the workpiece is dependent on the frequency of the arcing. Many small sparks (higher frequency) will give a smoother finish than fewer large sparks. An electrode with a melting point substantially greater than that of the workpiece will have a low wear ratio, whereas an electrode with a lower melting temperature will have a higher wear ratio.

Preparation of Electrode Blanks

It was necessary to produce two sets of electrodes to be used for the electrical discharge machining of the toothed forging die. The first set was for EDMing the die for the near-net teeth, with allowances for machining stock on the teeth. The second set was for preparing the die for the net teeth with no allowances for machining stock. The choices for electrode material were reduced to two, brass and graphite. Brass electrodes are easily machined and produce a very fine surface finish that is desirable for forge tooling. The drawback to brass is the wear ratio of electrode material removed compared to die material removed, which is approximately one to one. Graphite electrodes, on the other hand, even though they machine with more difficulty, offer many advantages. The most significant advantage is that the wear ratio of the die material to electrode material exceeds 5 to 1. The surface finish obtained from graphite is as fine if not finer than brass. Graphite is also lighter than brass which facilitates handling during machining of the blank and reduces weight on the ram during EDM. The cost of graphite is higher than that of brass. However, considering the metal removal rate of graphite as compared to brass, the overall cost of graphite electrodes is less. Considering these facts, graphite was selected as the material for the electrodes.

The graphite selected for the near-net tooth electrode was Union Kostkutter 10. This electrode material was chosen because of its good resistance to wear and it was readily available in a large round stock size. The graphite selected for the net tooth electrode was Mor-Wear EC-15. This material was selected because of smaller particle size and because it offers the advantage of producing a finer surface finish in the die cavity. The electrode blanks for both trials were turned in a lathe using normal machine practices. The electrode blank is shown in Figure A-1.

Cutting the Tooth Form

The tooth form was cut into the electrode blank using a #28 Gleason gear generator. The settings of the gear cutting machine were obtained from the output of the computer program SPBEVL, which was developed in Phase I of this project. For the near-net gear, the dimensions which were used to cut the teeth reflect a 0.007 inch (0.178 mm) machining allowance on the teeth. The settings on the #28 Gleason gear generator for cutting the near-net electrode are shown in Table A-1.

Different machine settings were used to cut the electrodes for the net teeth, where no machining allowances were considered. The machine settings for the net teeth electrodes are shown in Table A-2. The first step in cutting the electrodes was the development of a finish form-cut master set of gears. This procedure is common in developing any new set of gears. The masters are developed by first cutting the gear. The gear is cut to the theoretical dimensions for form, chordal thickness and spiral angle by using a standard spread blade cutter, which cuts both sides of the teeth at the same time. The next step is the development of the pinion. A master gear having a thinner tooth is cut with the proper tooth form but with a thin chordal thickness to allow the pinion to roll with the gear on one tooth flank at a time. This allows for development of both the drive and coast side without interference from the other side. All modifications of the gear set to obtain the proper bearing, profile, and position of bearing are made on the pinion. These developed masters are then used as a means of checking the electrodes.

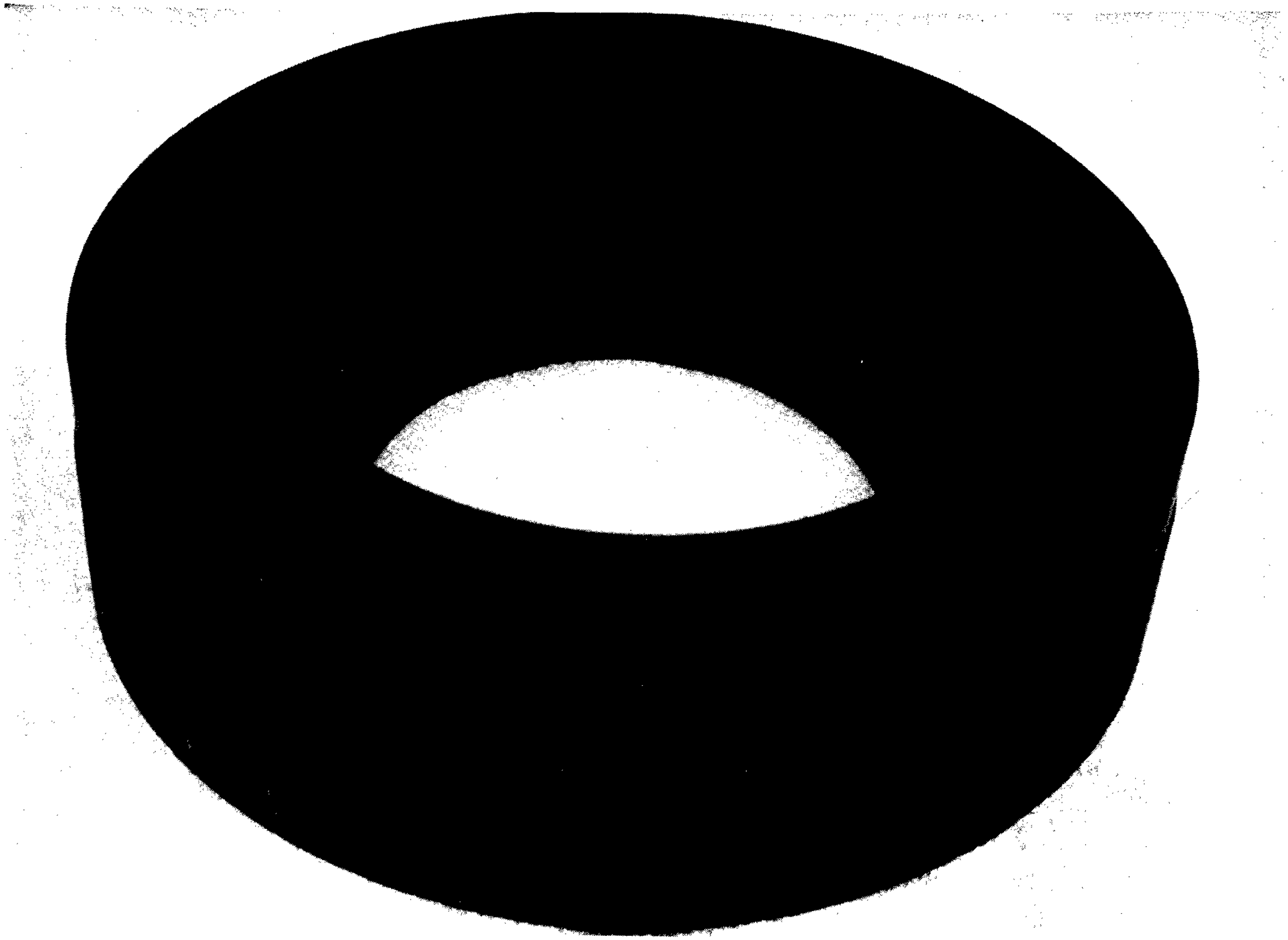

FIGURE A-1. Electrode Blank

TABLE A-1. Machine Setting for Cutting the Electrodes for Near-Net Teeth Forging

BLANK DIMENSIONS

Number of Teeth	39
Pressure Angle	20D
Spiral Angle	40D
Face Angle	81D08M04S
Pitch Angle	79D50M13S
Dedendum Angle	4D14M32S
Outer Cone Distance	5.181 Inch (131.6 mm)
Face Width	1.456 Inch (36.98 mm)
Addendum	0.075 Inch (1.91 mm)
Dedendum	0.384 Inch (8.84 mm)
Distance Between Crossing Point and Cone Apex	0.000 Inch
Mounting Distance	2.036 Inch (51.71 mm)

CUTTER DATA

Cutter Diameter	9.179 Inch (233.2 mm)
Point Width	0.144 Inch (3.658 mm)
Outside Blade Angle	20D04M43S
Inside Blade Angle	19D59M21S
Outside Blade Radius	0.076 Inch (1.93 mm)
Inside Blade Radius	0.076 Inch (1.93 mm)

MACHINE SETTINGS

Machine Root Angle	77D10M31S
Machine Center to Back	-0.140 Inch (-3.556 mm)
Sliding Base	0.007 Inch (.178 mm)
Blank Offset	0.000 Inch
Eccentric Angle	32D42M16S
Cradle Angle	228D28M38S
Decimal Ratio	0/0/0/0

TABLE A-2. Machine Settings for Cutting the Electrodes for Net Teeth Forging

BLANK DIMENSIONS	OLD VALUES	NEW VALUES
Number of Teeth	39	39
Pressure Angle	20DOM	20DOM
Sprial Angle	40DOM	40DOM
Face Angle	81D7M	81D7M41S
Pitch Angle	79D49M	79D49M47S
Dedendum Angle	4D15M	4D14M42S
Outer Cone Distance	5.080 Inch (129.0 mm)	5.190 Inch (131.8 mm)
Face Width	1.428 Inch (36.27 mm)	1.459 Inch (37.06 mm)
Addendum	.074 Inch (1.88 mm)	.076 Inch (1.93 mm)
Dedendum	.377 Inch (9.58 mm)	.385 Inch (9.78 mm)
Distance Between Crossing Point and Come Appex	0.000 Inch	0.000 Inch
Mounting Distance	2.000 Inch (50.80 mm)	2.041 Inch (51.84 mm)
CUTTER DATA		
Cutter Diameter	9.000 Inch (228.6 mm)	9.195 Inch (233.5 mm)
Point Width	.150 Inch (3.81 mm)	.156 Inch (3.96 mm)
Outside Blade Angle	20DOM	20D2M60S
Inside Blade Angle	20DOM	19D59M35S
Outside Blade Radius	.060 Inch (1.52 mm)	.061 Inch (1.55 mm)
Inside Blade Radius	.060 Inch (1.52 mm)	.061 Inch (1.55 mm)
MACHINE SETTINGS		
Machine Root Angle	77D9M	77D9M58S
Machine Center to Back	MD-.138 Inch (3.50 mm)	MD-.141 Inch (3.58 mm)
Sliding Base	0.000 Inch	ADV-.003 Inch (0.076 mm)
Blank Offset	0.000 Inch	0.000 Inch
Eccentric Angle	32D3M	32D45M53S
Cradle Angle	228D9M	228D30M27S
Decimal Ratio	0/0/0/0	0/0/0/0

The electrodes were cut using EDM dielectric fluid as the gear cutting coolant. The graphite used for the electrodes is porous in its composition. Any coolant used during cutting of the teeth will be absorbed by the graphite. If a standard cutting fluid is used, the oil will not be compatible with the EDM process. Using dielectric fluid eliminates this problem. Figure A-2 shows the electrode while the teeth are being cut. Figure A-3 shows the electrode after machining.

Manufacturing of the Dies Using EDM

The gear impression of the die is obtained by EDMing. Electric discharge machining was selected as the method of reproducing the electrode impression in the die because of the accuracy of reproduction. EDM is advantageous since it can be used after the tool material has been hardened. This will assure the die impression to be correct without the fear of distortion from heat treatment. The machine used was a Charmilles Model 400 EDM. The electrode was mounted on an arbor which was attached to the top platen of the ram. The ram was fed straight down to the die blank. The gear configuration is such as to allow sinking the die without rotation of the electrode.

The EDM operation consisted of using six (6) electrodes in sequence. Each subsequent electrode was used to sink deeper until the required depth was obtained. Figure A-4 shows the dies being EDMed.

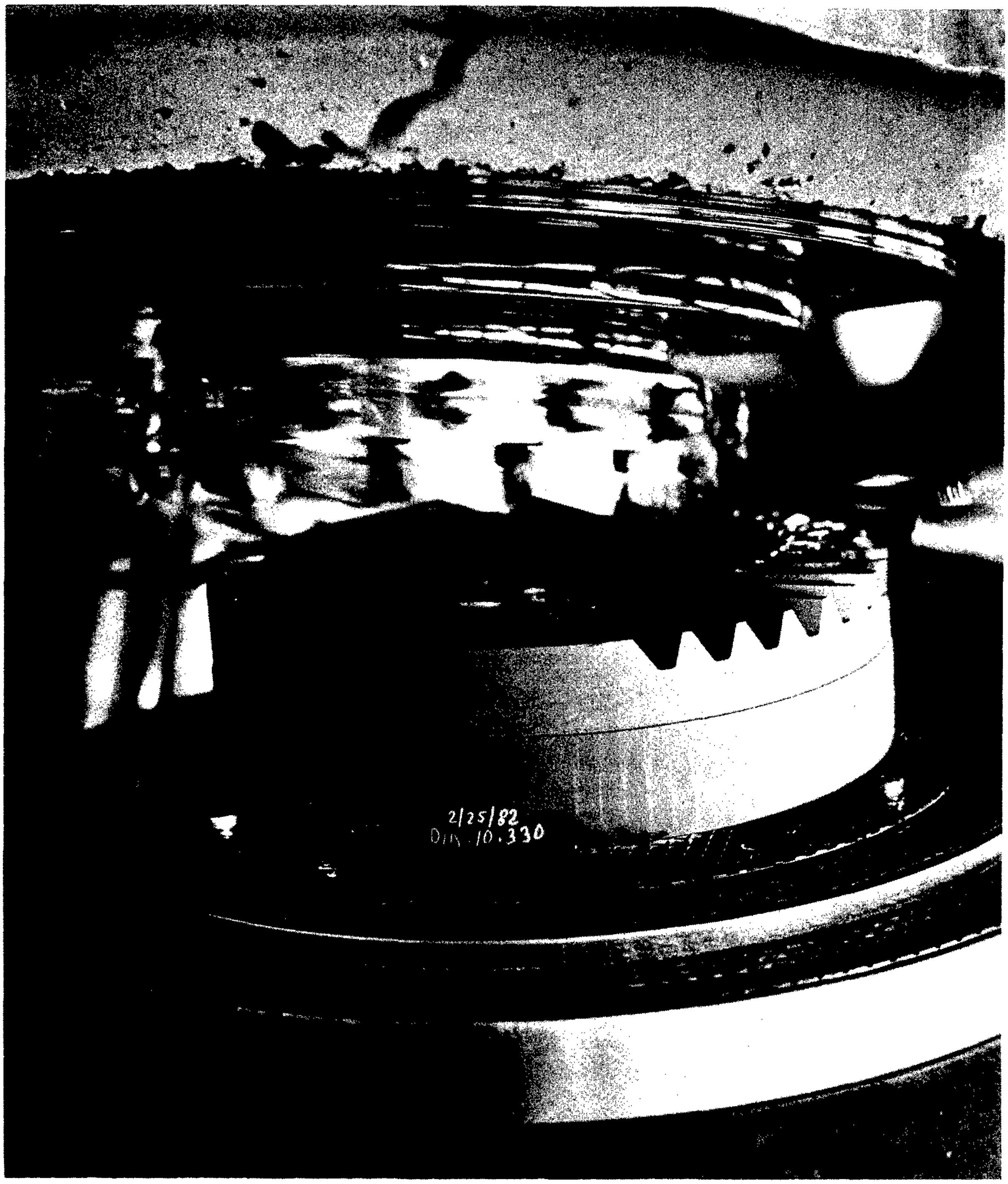

FIGURE A-2. Machining of Electrodes

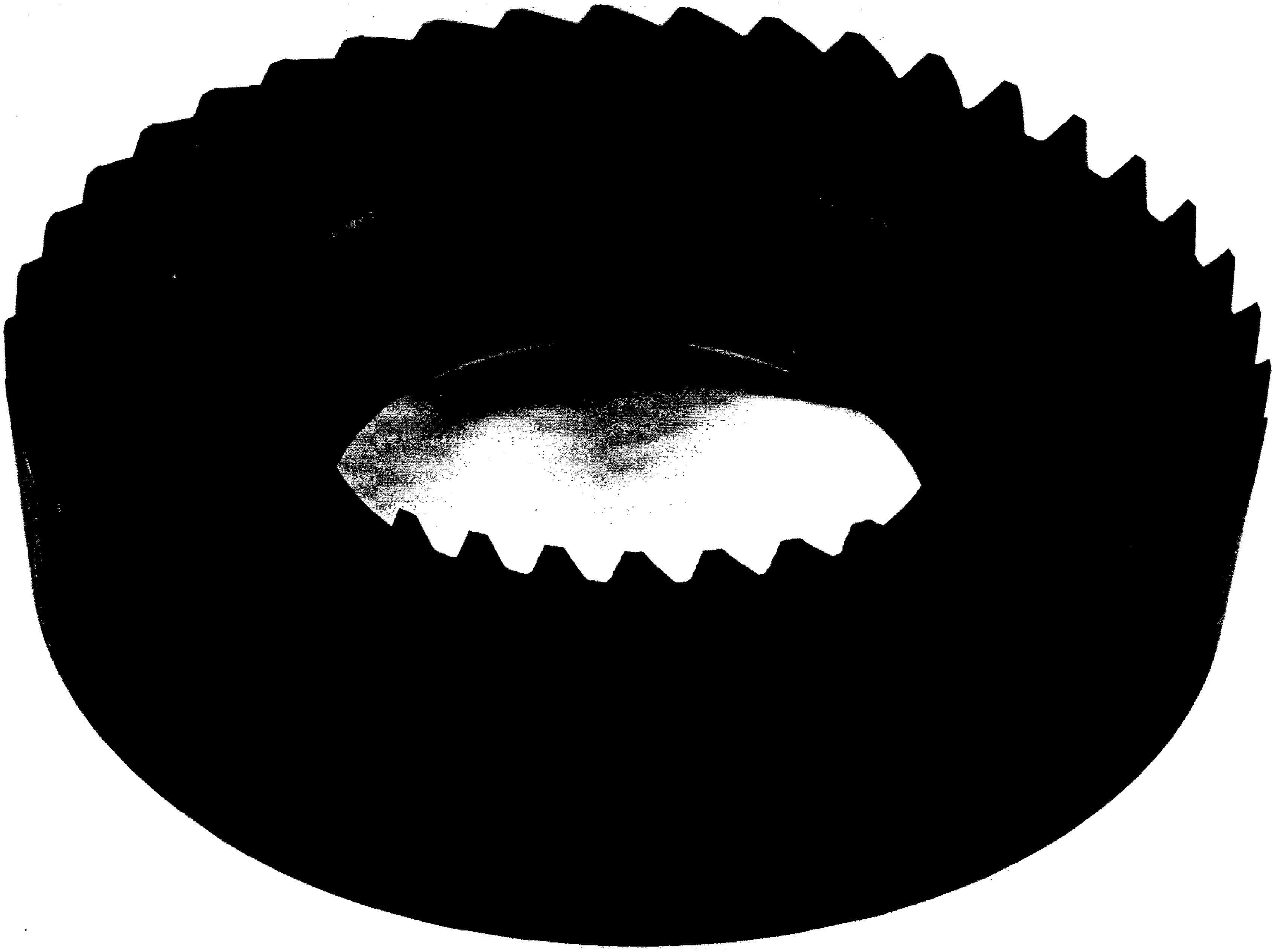

FIGURE A-3. The Electrode After Machining

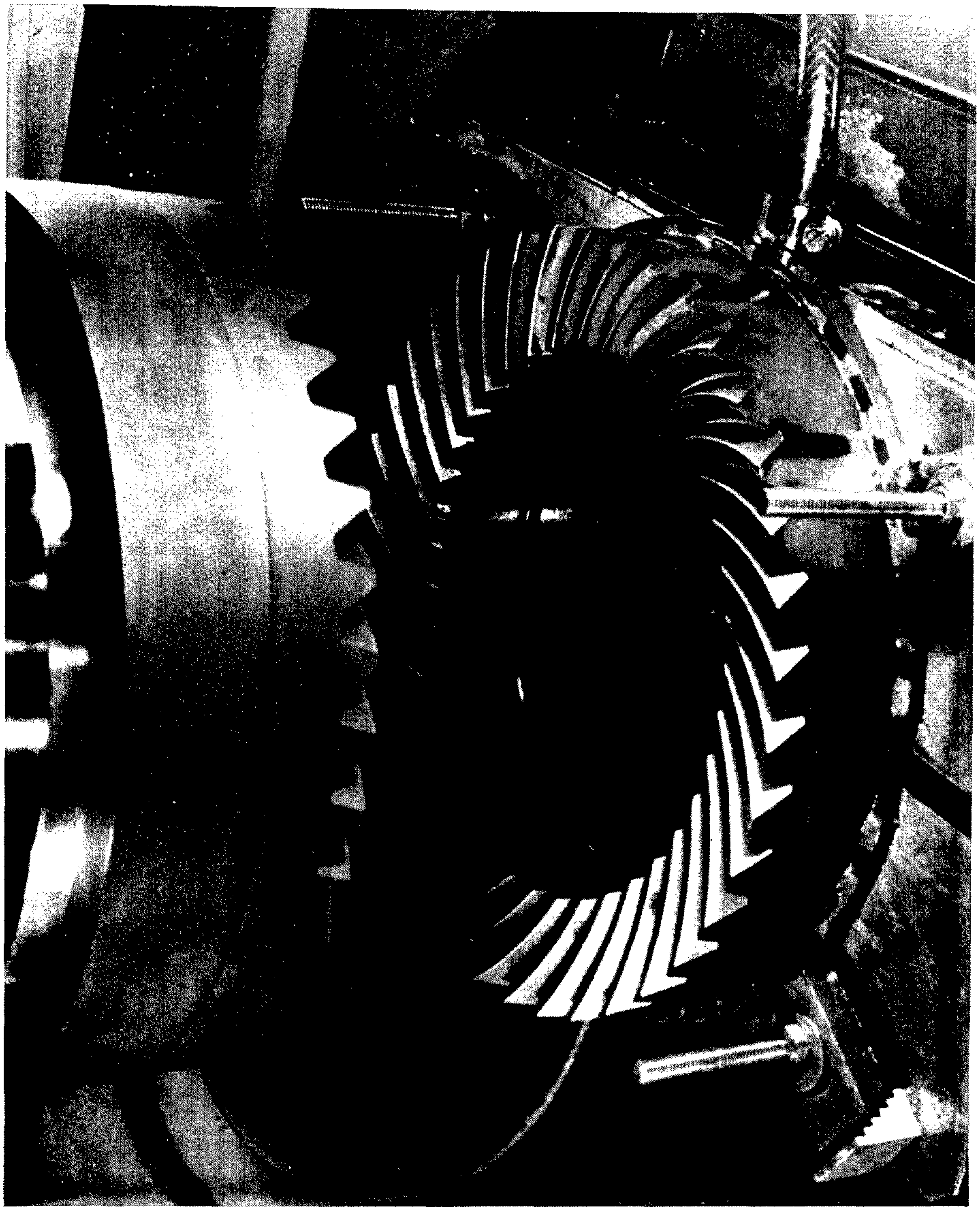

FIGURE A-4. Dies Being EDMed

REFERENCES

1. Tool Steels Catalog, Universal Cyclops Speciality Steel Division, 650 Washington Road, Pittsburgh, Pennsylvania 15228.

2. Lange, K., "Textbook of Metal Forming", Volume 3, Springer Verlag, 1974.

APPENDIX B

FORGING TRIALS

APPENDIX B

FORGING TRIALS

The gear forging trials were conducted at Eaton Corporation's Forging Division in Marion, Ohio. A 3,000-ton forging press, manufactured by National Machinery Company, Tiffin, Ohio, was used for the trials. The press, shown in Figure B-1, was selected based upon the anticipated forging load of about 2,500 tons and the space available for tooling. The forging dies used in the trials are shown schematically in Figure 11. As can be seen in this figure, metal flow into the flash is provided radially, inward only.

The metal is trapped at the outside diameter of the forging. The forging tooling is all contained in die holders mounted on top and bottom bolsters. In the bottom die holder, the tooling contains the tooth form and represents the most critical portion of one tool assembly. (It may be more advantageous to put the tooth form into the top die assembly. Thus, the cooling effects would be reduced. However, this was not possible in the present press because a top ejector was not available.) Three series of trials were conducted to evaluate the techniques developed during this project.

First Series of Forging Trials

The purpose of these trials was to evaluate the tooling design, determine the process variables and to identify potential problem areas. In this regard, the trials are considered to be successful. The gear forgings were successfully forged and ejected from the die and no damage to the tooling occurred. The process conditions for these forging trials are as follows:

Press - 3,000-Ton National
Billet Temperature - 2,000° F (1,093° C)
Die Temperature - 300° F (149° C)
Billet Coating - (1) None
(2) GP-158 Graphite Products
Die Lubricant - Pro-Chem TC 955-B

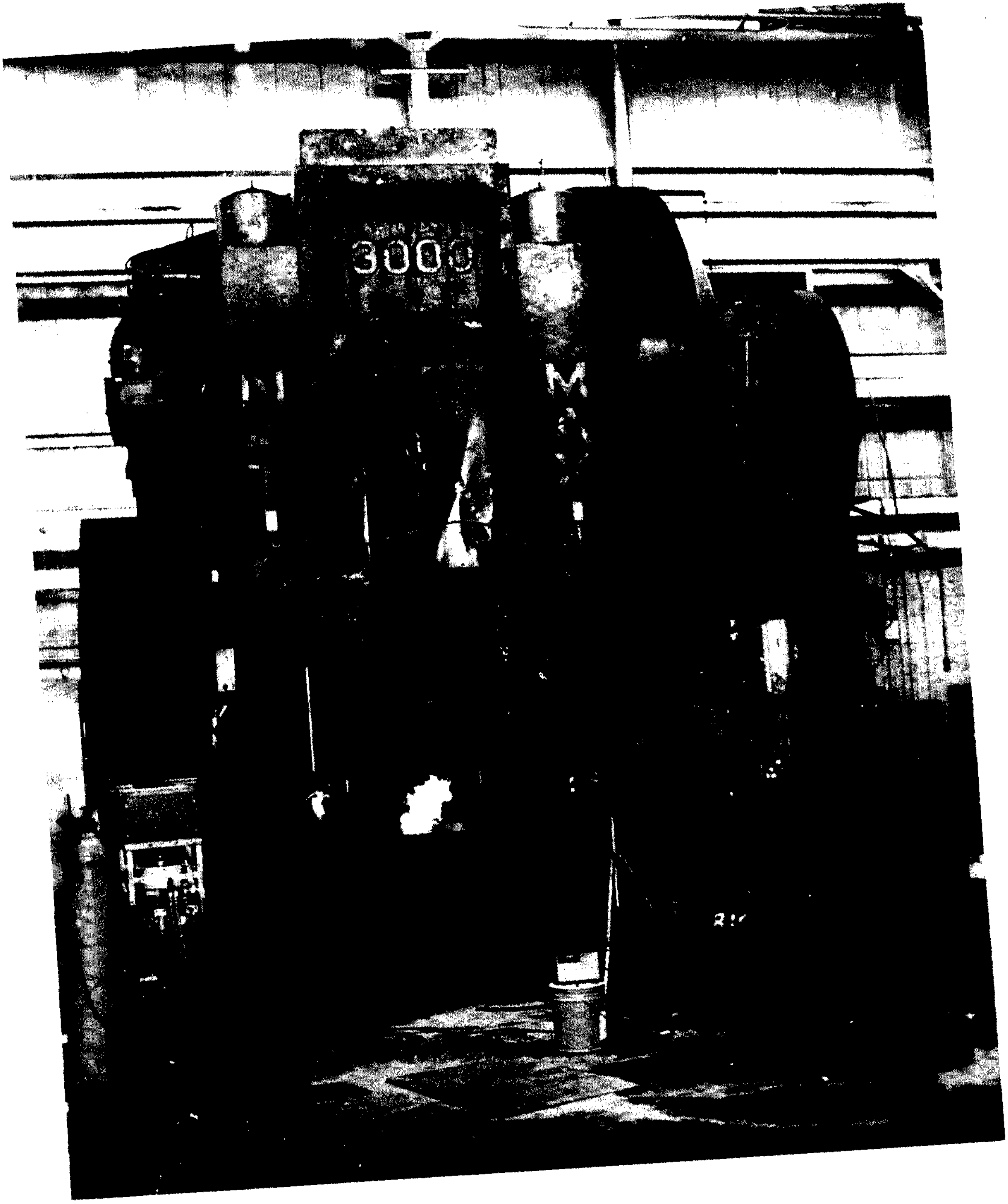

FIGURE B-1. Mechanical Press Used for Forging the Gears

Billet Heating - Gas-Fired Furnace with Nitorgen
as a Protective Atmosphere
Billet Material - 8620 Steel
Instrumentation - (1) Helm Load Monitor
(2) Ircon Radiation Temperature Monitor
Cooling Method - Sand and Graphite Mix

Twenty-one spiral bevel gears were forged. The fill of the gear teeth was in general not as good as desired. Based upon the results of these trials it was felt that there were two major reasons for not achieving the amount of fill desired, die design and scale. To improve the die design, the die was to be vented to allow entrapped gases and lubricants to escape. To reduce the amount of scale, it was planned to take the following measures for the next forging trials:

1. Use superior billet precoat prior to heating to reduce oxidation.
2. Use induction heating to heat the billet, as opposed to using a gas-fired furnace. The induction coil would have (a) an atmosphere to reduce oxidation, (b) provisions for precise temperature measurement while the preform is in the coil, and (c) sufficient power to heat the preform in less than five minutes.

The gears from Trials 1 were not evaluated for dimensional accuracy. The rough surface condition of the tooth flanks, due to scale, would have made measurements unreliable.

Second Series of Forging Trials

The second series of trials were directed at establishing the process parameters for forging gears with near-net teeth. The parts were heated in an induction heating coil with nitrogen as protective atmosphere. The coil was placed on the frame of a material handling mechanism which was used to lift the billet into the coil. The billet was placed on a high temperature refractory material which sealed the coil, allowing the neutral atmosphere to be trapped. An air cylinder was mounted under the coil to lift the billet into the coil. The coil was coupled to an induction generator which balances the voltage to permit uniform heating. The coil was tested successfully at the vendor prior to running the trials. The induction heating coil and material handling device are shown in Figure B-2.

The conditions for Trials II were as follows:

Forging Press - 3,000-Ton National
Billet Temperature - 2,000° F (1,093° C)
Die Temperature - 300° F (149° C)
Billet Coating - (1) Deltaforge 182 (Acheson)
(2) None
Die Lubricant - Deltaforge 31 (Acheson)
Billet Heating - Induction Heating with Nitrogen
as a Protective Atmosphere
(Induction Frequency = 1 K.Hz)*
Billet Material - 8620 Steel
Heating Time - 2.5 Minutes
Instrumentation - Helm Load Monitor
Cooling Method - Sand and Graphite Mix

Twenty-two parts were forged for the second series of trials. The results are summarized in Tables B-1 and B-2. Figure B-3 illustrates the method for evaluating die fill that is listed in Table B-2. Figures B-4, B-5 and B-6 were taken during the forging trials and show the temperature sensor, a forged part and the forging being cooled in the sand and graphite mix, respectively.

The forging trials were successful in producing gears with far better surface finish than those forged in the first trials. The induction heating of the preforms produced forgings with minimal scale. The die design and ejection mechanism worked without any difficulty,allowing the

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* This frequency was used because the available generator had a high frequency range; however, in real production, the frequency to be used should be between 60 to 100 Hz, because the depth of current penetration varies inversely as the square root of the frequency of the current. Therefore, a through heating application, such as for forging, requires generally lower frequencies than for surface hardening, brazing or soldering.

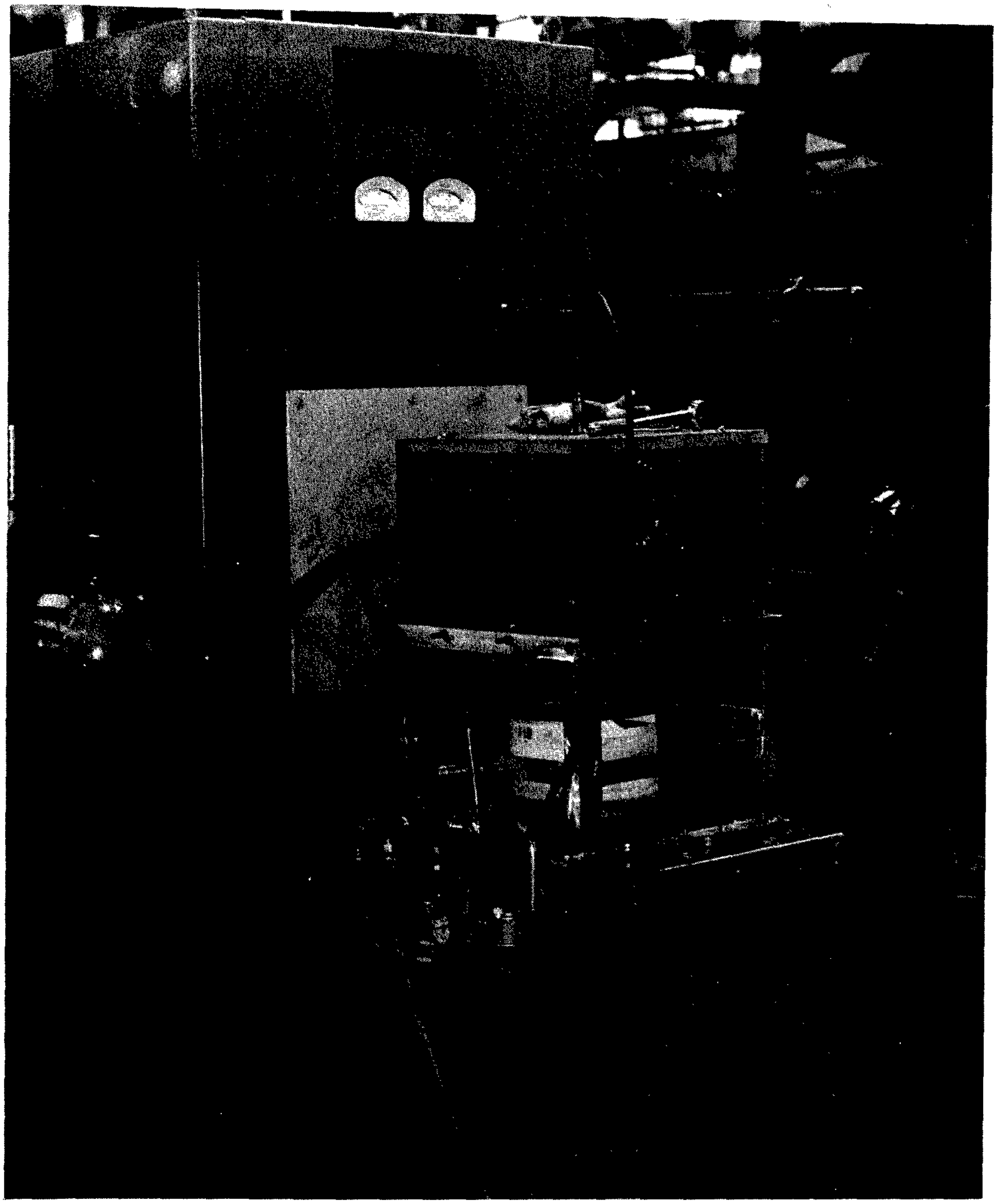


FIGURE B-2. The Induction Coil Set-Up Used in the Second and Third Series of Forging Trials

TABLE B-1. Forging Trials (Second Series)

Date of Trials: 1/13/82 Location: Forge/Marion

Trial	Pre-Coat	Billet Temp.		Tonnage	1000 kg	Part Thickness		Comments
		°F	°C			in	mm	
2-1	DF-182	2,015	1,102	--	--	--	--	Did not forge
2-2	"	2,011	1,099	2,458	2,230	.610	15.5	Water-cooled
2-3	"	2,022	1,106	2,930	2,658	.595	15.1	
2-4	"	--	--	--	--	--	--	Did not forge
2-5	"	2,033	1,112	2,970	2,694	.595	15.1	
2-6	"	2,015	1,102	2,906	2,636	"	"	New operator
2-7	"	1,998	1,092	2,892	2,624	"	"	
2-8	"	1,970	1,077	2,860	2,595	"	"	
2-9	"	2,013	1,101	2,906	2,636	"	"	
2-10	"	1,950	1,066	2,856	2,591	"	"	Original operator
2-11	"	1,998	1,092	2,836	2,573	"	"	Started placing flame ring in die after every piece
2-12	"	1,998	1,092	2,861	2,596	"	"	
2-13	"	2,015	1,102	2,856	2,591	"	"	
2-14	"	2,124	1,162	2,861	2,596	"	"	
2-15	"	2,033	1,112	2,814	2,553	"	"	Coil allowed to cool before trial
2-16	None	1,978	1,081	2,800	2,540	"	"	Temp. after forge - 1684
2-17	"	2,016	1,102	2,884	2,616	"	"	Temp. after forge - 1774
2-18	"	1,960	1,071	2,864	2,598	"	"	
2-19	"	2,005	1,096	2,840	2,576	"	"	
2-20	"	2,036	1,113	2,861	2,595	"	"	
2-21	"	2,005	1,096	2,860	2,595	"	"	
2-22	"	1,984	1,084	2,851	2,586	"	"	Part was reheated
2-23	"	2,012	1,100	2,854	2,589	"	"	
2-24	"	2,001	1,094	2,894	2,625	"	"	

TABLE B-2. Evaluation of Forged Gears (Second Series)

Date of Trials: 1/13/82 Location: Forge/Marion

Trial Number	$\underline{\alpha}$ Length of Flat at Top of Tooth that is Filled* in	mm	% Fill α/β*
2-7	1.372	34.85	71.6
2-8	1.112	28.24	58.1
2-9	1.415	35.94	73.9
2-10	1.282	32.56	67.0
2-11	1.415	35.94	73.9
2-12	1.335	33.91	69.7
2-13	1.462	37.13	76.4
2-14	1.543	39.19	80.6
2-16	1.399	35.53	73.0
2-17	1.382	35.10	72.2
2-18	1.248	31.70	65.2
2-19	1.345	34.16	70.2
2-22	1.396	35.46	72.9
2-23	1.365	34.67	71.3
2-24	1.428	36.27	74.6

* Total length of tooth top (β) was 1.915 inch (48.64 mm), as seen in Figure B-3

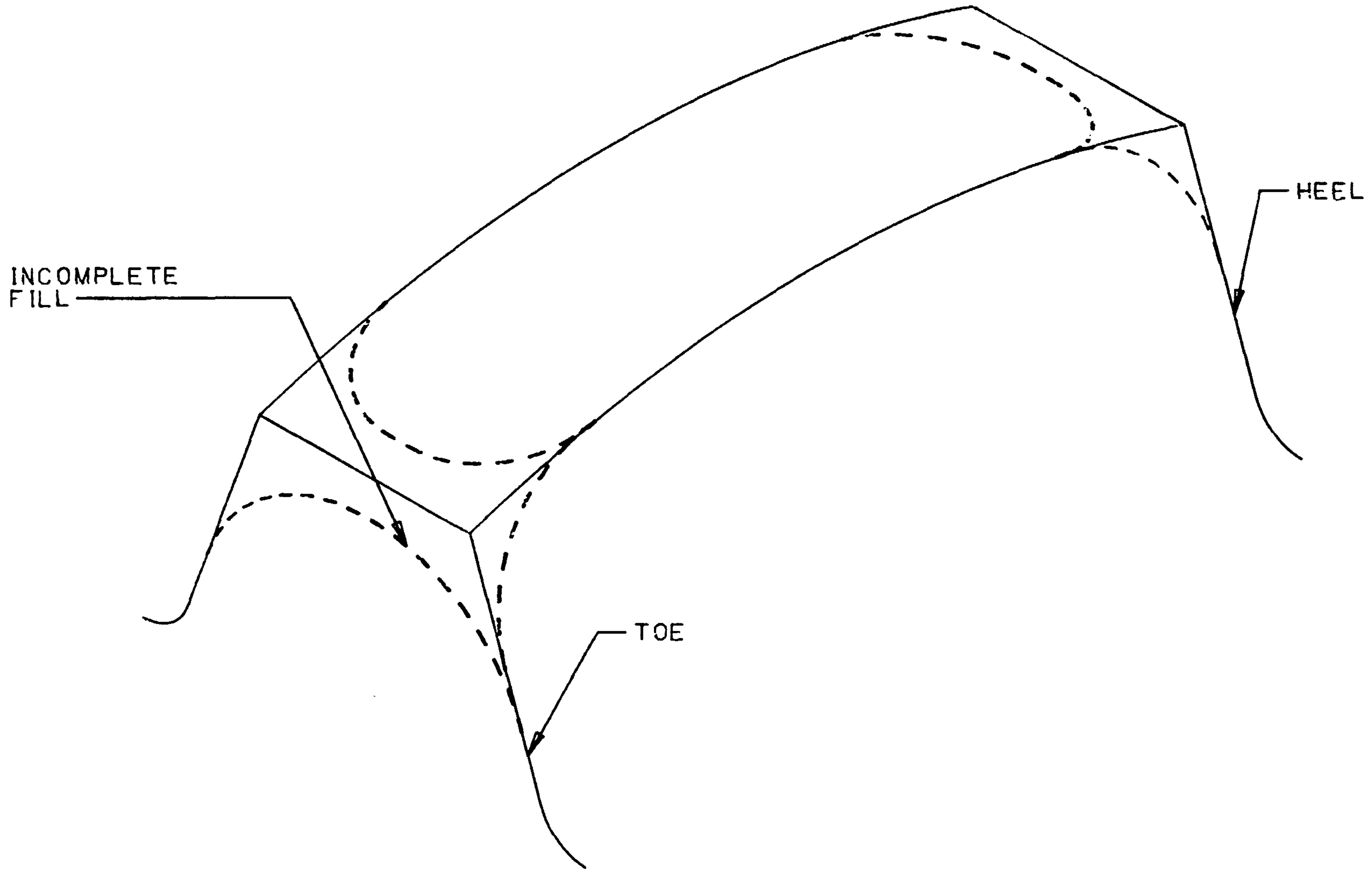


FIGURE B-3. Length of Filled Part at Top of Tooth (α), and Total Length at Top of Tooth (β)

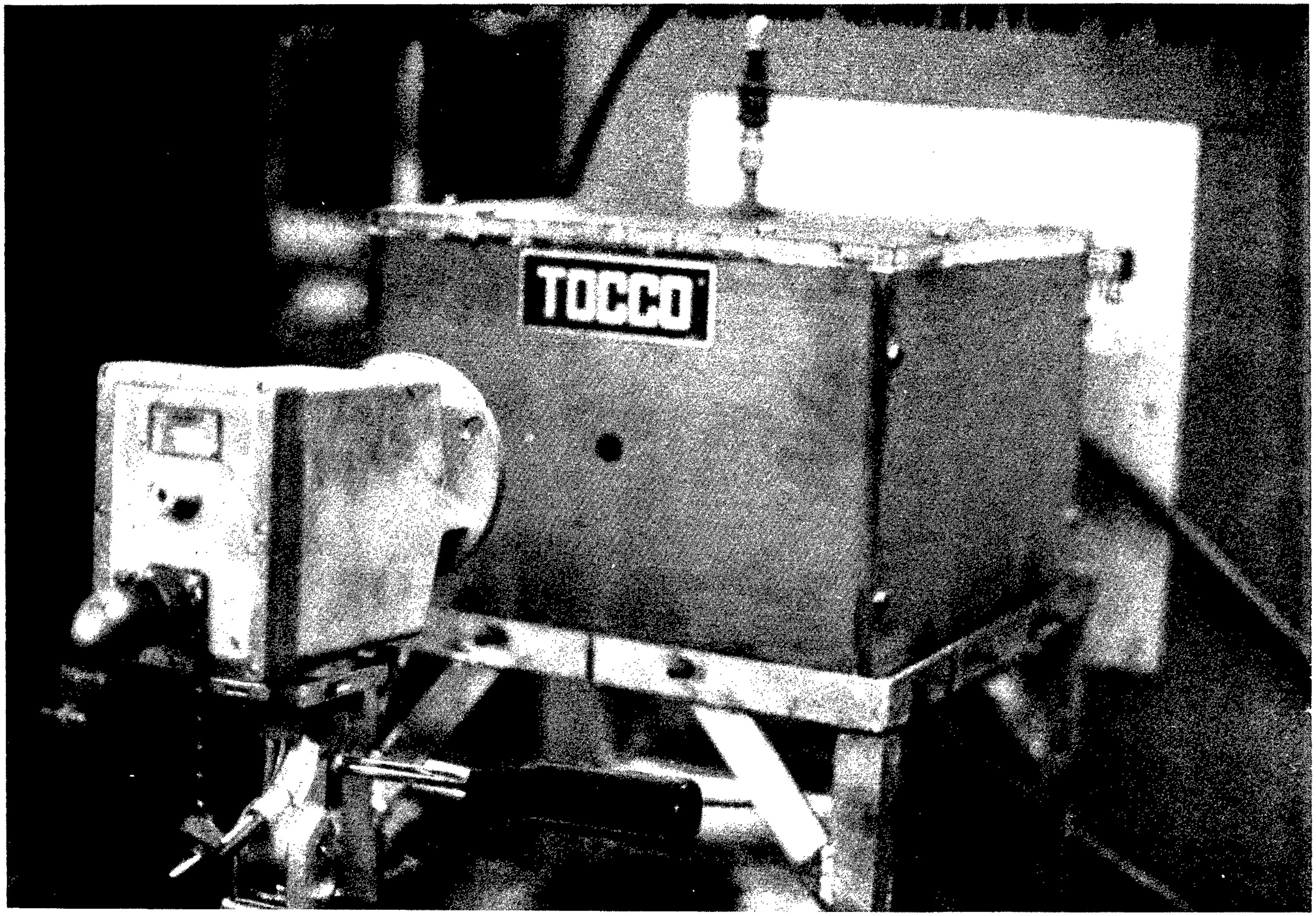


FIGURE B-4. Radiation Temperature Sensor Oriented Toward the Heating Coil
(A peek hole is provided in the box surrounding the coil)

FIGURE B-5. Forged Gear Coming Out of Die After Forging Blow

FIGURE B-6. Forged Gears Cooled (Face Down) in a Sand-Graphite Mixture part to be easily removed form the die. The dies were preheated with a circular flame ring that fit into the die cavity as shown in Figure B-7. This assured uniform heating of the die before forging. The flame ring was placed around the die, while preforms were being heated, in order to keep the die as warm as possible to minimize chilling and enhance filling. (In production, it may be advantageous to have a built-in electric heating or a die holder design that provides cooling and heating with a circulating fluid.)

The teeth of the forgings were not filled 100% in the toe and heel. The design of the radii on the preform did not allow enough material in these areas to insure complete filling. A new preform was designed and manufactured for use in the third series of trials for obtaining net forged teeth (refer to the section on "Preform Design" of the main text of this report).

The preforms were heated by induction, which heats from the outside into the center of the part. To obtain a uniform temperature throughout the part, it was necessary to alternate heating and non-heating cycles. The method followed was heat 2 minutes, soak in coil 30 seconds, heat 30 seconds, soak in coil 30 seconds, then remove from coil and forge. The heating time of 2.5 minutes, given earlier, reflects this heating approach.

Third Series of Trials

These trials were performed to forge the gears with net teeth. The parts were heated in an induction heating coil with nitrogen serving as an inert atmosphere. The billets were not precoated prior to heating since billets without coating did not scale in Trials II. The coil and lifting mechanism was the same as those used in Trials II. The preform temperature was monitored during heating by means of a sight hole in the coil. The billet was heated to 1,930° F (1,054° C), then allowed to have the heat soak throughout the part until the outside of the ring-type preform was 1,700° F (926.7° C). The part was reheated to 2,100° F (1,148.9° C), allowed to soak until it was down to 2,000° F (1,093° C), then forged. This heat/soak procedure was necessary because the induction process heats the outside of the part first with heat subsequently flowing towards the center. If this

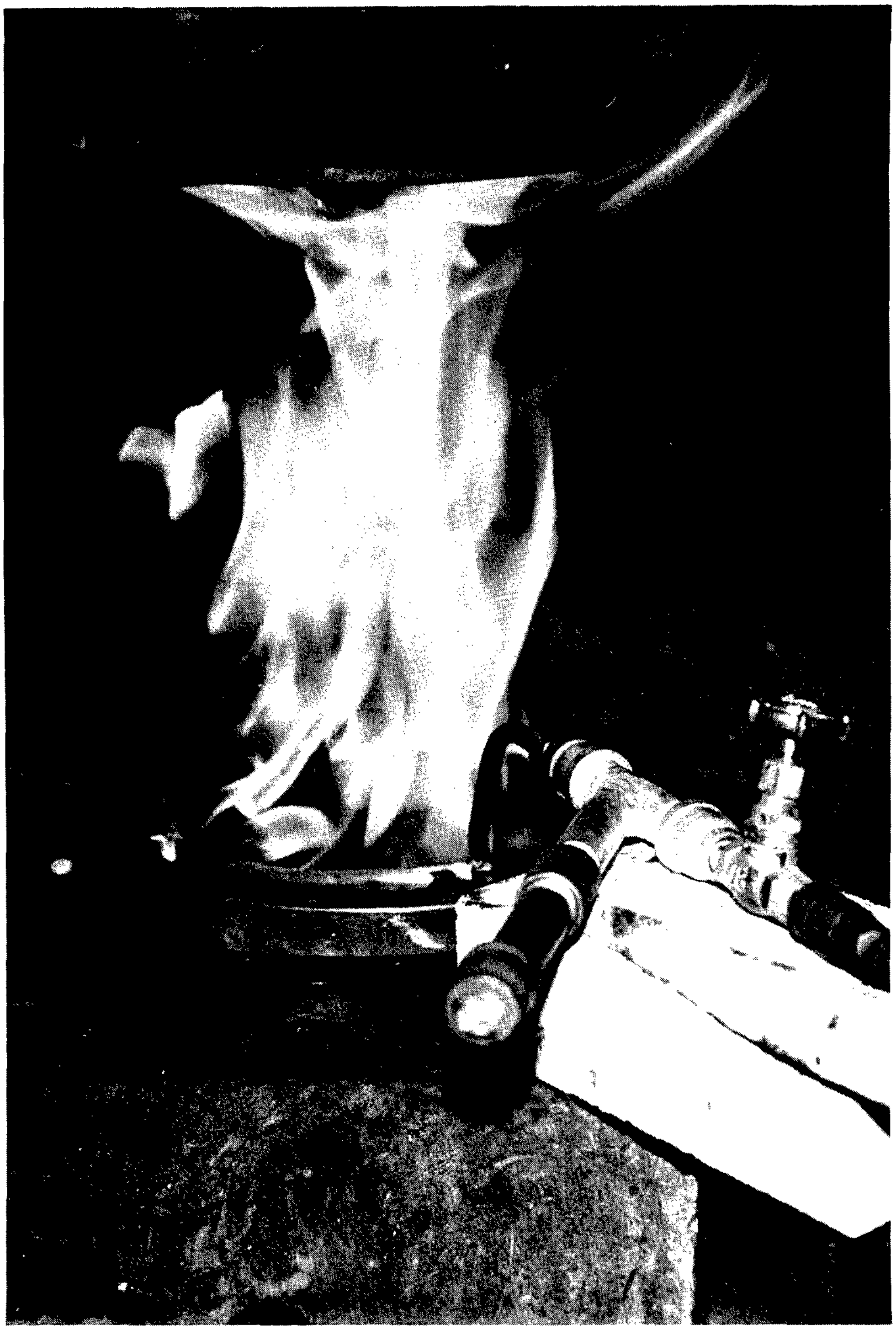


FIGURE B-7. Heating of the Dies With a Circular Gas Flame heating method is not followed, the center may be too cold to forge even through the outside may be hot enough or overheated.

The parameters for Trials III were as follows:

Forging Press - 3,000-Ton National
Billet Temperature - 2,000° F (1,093° C)
Die Temperature - 300° F (149° C)
Billet Coating - None
Die Lubricant - Deltaforge 31 (Acheson)
Billet Heating - Induction Heating with Nitrogen
as a Protective Atmosphere
(Frequency = 1 K.Hz)
Billet Material - 8620 Steel
Instrumentation - (1) Helm Load Monitor
(2) Ircon Radiant Temperature Sensor
Cooling Method - Sand and Graphite Mix.

Twenty-three parts were forged during the third series of trials. The results are shown in Tables B-3 and B-4. The preform types, used in these trials were identified as A,B and C. The dimensions of these preforms are given in Figures B-8, B-9 and B-10. The newly designed preform for these trials, preform type B of Figure B-9, was the most successful preform design for producing the maximum fill condition. A cleaned forging with net forged teeth, is shown in Figure 18.

TABLE B-3. Forging Trials (Third Series)

Date of Trials: 3/15/82 Location: Forge Marion

Trial	Preform[2]	Billet Temp. Before Forging °F	Billet Temp. Before Forging °C	Forging Load Tons	Forging Load 1000 kg	Shims[1] in	Shims[1] mm	Heat Time	Comments
3-1	A	2,000	1,093	1,201	1,089	.330	8.382	*	Part in die wrong
3-2	A	"	"	1,285	1,166	"	"	*	
3-3	A	"	"	1,268	1,150	"	"	*	
3-4	B	"	"	1,661	1,507	"	"	*	
3-5	B	"	"	2,154	1,954	.390	9.906	*	
3-6	C	"	"	2,136	1,938	"	"	*	
3-7	B	"	"	2,461	2,233	.435	11.049	*	
3-8	B	"	"	2,435	2,209	"	"	*	
3-9	B	"	"	2,393	2,171	"	"	*	
3-10	B	"	"	2,386	2,165	"	"	*	
3-11	B	"	"	2,363	2,144	"	"	*	
3-12	B	"	"	2,361	2,142	"	"	*	
3-13	A	"	"	1,951	1,770	"	"	*	
3-14	B	"	"	2,351	2,133	"	"	*	
3-15	B	"	"	2,396	2,174	"	"	*	
3-16	A	*	*	*	*	"	"	2.5 Min.	Heating time
3-17	A	1,842	1,006	1,897	1,721	"	"	4.5 Min.	
3-18	A	1,983	1,084	1,912	1,735	"	"	5.0 Min.	
3-19	B	2,006	1,097	2,414	2,190	"	"	*	
3-20	B	2,000	1,093	2,350	2,132	"	"	*	
3-21	B	"	"	2,333	2,116	"	"	*	
3-22	B	"	"	2,333	2,116	"	"	*	
3-23	C	"	"	2,417	2,193	"	"	*	
3-24	A	"	"	1,944	1,764	"	"	*	

[1] "Shims" is the amount of shimming placed behind the punch to vary the thickness of the forging. Shims, therefore, change the thickness of the forging as well as fill of the part.

[2] Three preform shapes were used, as discussed in the main text of the report. The preform configurations are seen in Figures B-8, B-9 and B-10 for preform types A, B, and C, respectively.

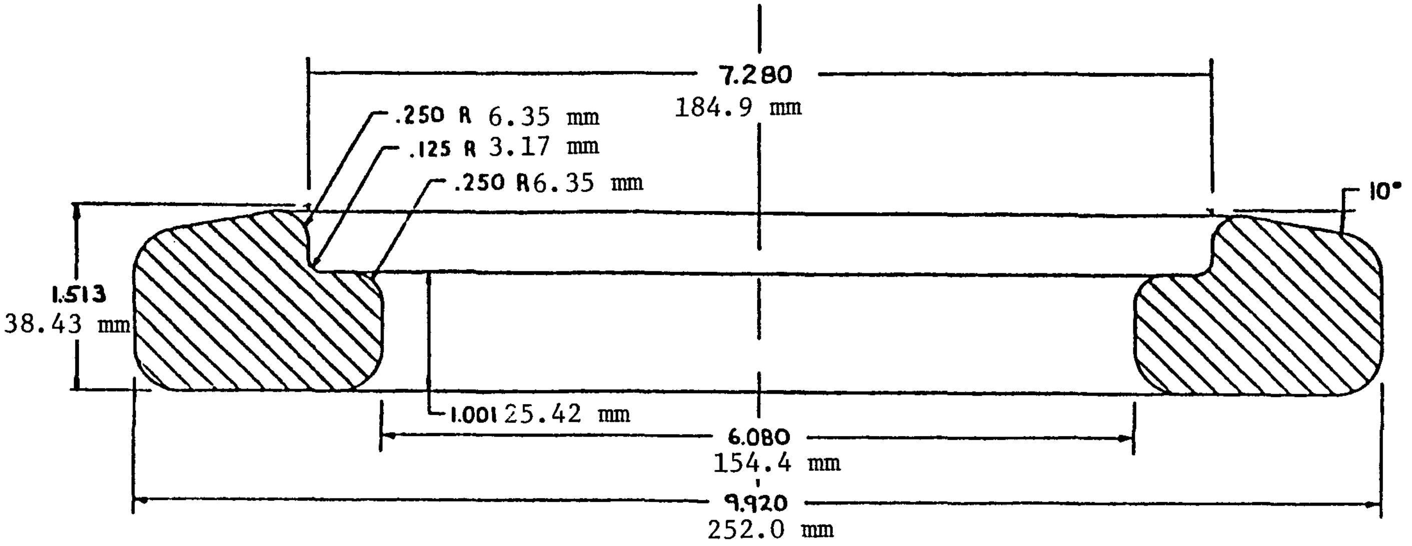
*Not measured

TABLE B-4. Evaluation of Forged Gears (Third Series)

(Preforms A, B and C are seen in Figures B-8, B-9 and B-10, respectively. For α and β, see Figure B-3.)

Sample	Preform Design	Thru Bore Thickness in	Thru Bore Thickness mm	α Length of Flat at Top of Tooth Filled in	α Length of Flat at Top of Tooth Filled mm	β Total Length Top of Tooth in	β Total Length Top of Tooth mm	% Fill α/β
3-1	A	0.620-0.622	15.75-15.80	*	*	1.915	48.64	*
3-2	A	0.617-0.623	15.67-15.82	*	*	"	"	*
3-3	A	0.625-0.634	15.88-16.10	*	*	"	"	*
3-4	B	0.662-0.674	16.81-17.12	0.500	12.72	"	"	26.1
3-6	C	0.660-0.661	16.76-16.79	*		"	"	*
3-7	B	0.654-0.658	16.61-16.71	1.415	35.94	"	"	73.9
3-8	B	0.655-0.658	16.64-16.71	1.400	35.56	"	"	73.1
3-9	B	0.655-0.657	16.64-16.69	1.300	33.02	"	"	68.0
3-10	B	0.649-0.652	16.48-16.56	1.440	36.58	"	"	75.2
3-11	B	0.652-0.653	16.56-16.59	1.425	36.20	"	"	74.4
3-12	B	0.647-0.652	16.43-16.56	1.510	38.35	"	"	78.9
3-13	A	0.617-0.619	15.67-15.72	1.295	32.89	"	"	67.6
3-14	B	0.646-0.654	16.41-16.61	1.560	39.62	"	"	81.5
3-15	B	0.652-0.653	16.56-16.59	1.600	40.64	"	"	83.6
3-17	A	0.614-0.617	15.60-15.67	1.285	32.77	"	"	67.1
3-18	A	0.610-0.618	15.49-15.70	1.445	36.83	"	"	75.5
3-19	B	0.649-0.656	16.48-16.66	1.555	39.50	"	"	81.2
3-20	B	0.649-0.653	16.48-16.59	1.390	35.31	"	"	72.6
3-21	B	0.649-0.656	16.48-16.66	1.380	35.05	"	"	72.1
3-22	C	0.660-0.661	16.76-16.79	*	*	"	"	*
3-23	A	0.608-0.612	15.44-15.54	1.257	31.93	"	"	65.6

*Not measured



Note: Radii .375 in. (9.525 mm) unless otherwise noted
Preform material is 8620 steel

FIGURE B-8. Preform Design (Type A) Used in Near-Net and Net Forging Trials (Second and Third Series)

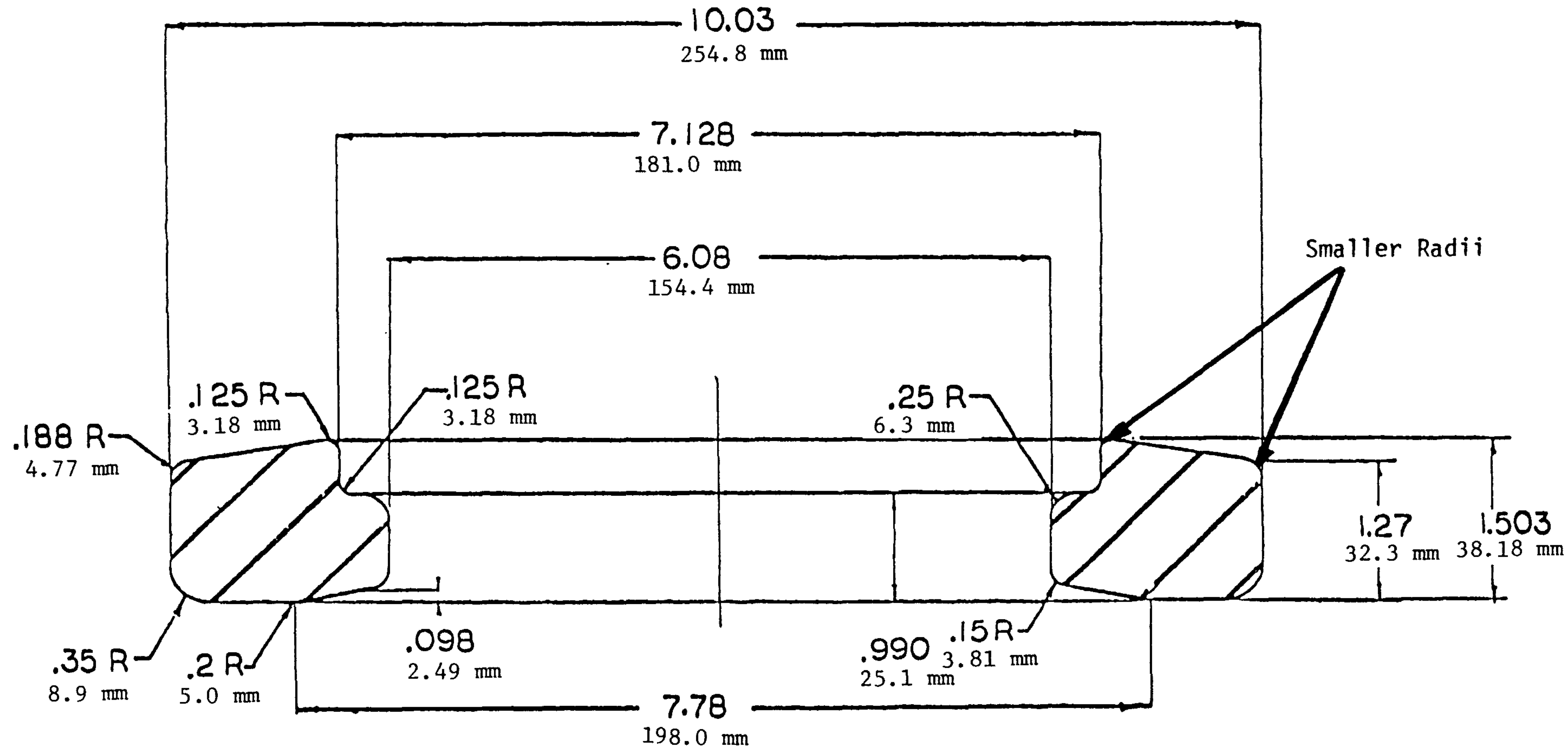


FIGURE B-9. Preform Design (Type B) Used in Net Forging Trials (Third Series)
(Preform material: 8620 steel)

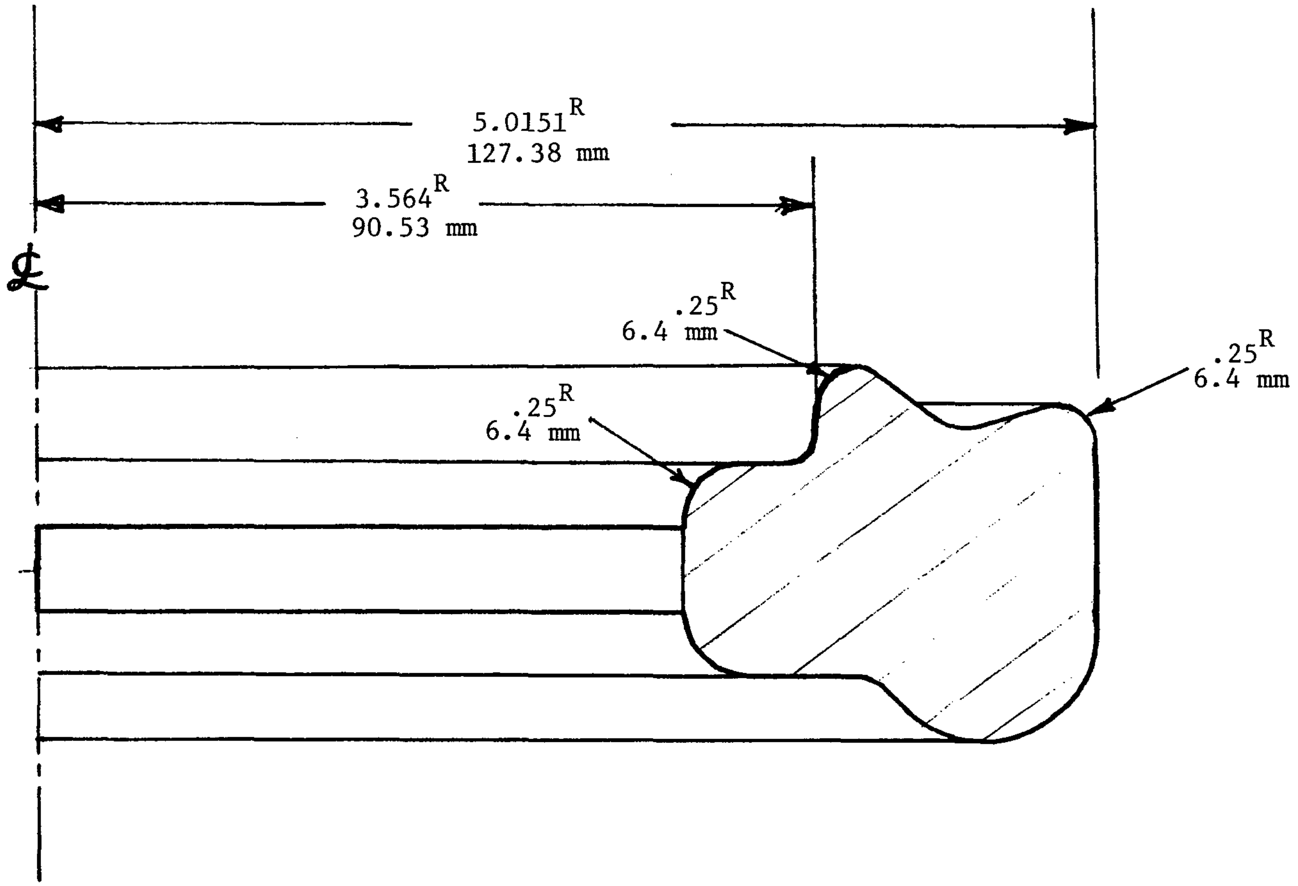


FIGURE B-10. Experimental Preform Used in Net Forging Trials
(Preform material: 8620 steel)

APPENDIX C

MACHINING AND DIMENSIONAL EVALUATION OF FORGED GEARS

APPENDIX C

MACHINING AND DIMENSIONAL EVALUATION OF FORGED GEARS

Cooling and Cleaning of Forged Gears

The forged gears were cooled in a mixture of sand and powdered graphite. This method of cooling was chosen to minimize distortion due to cooling and reduce the amount of scaling due to oxidation. The graphite is a part of the mixture so that when it comes in contact with the hot gear it forms gaseous carbon dioxide, CO_2. This carbon dioxide forms a reducing atmosphere around the teeth that minimizes scaling and decarbonization. It is important to have minimal scale to evaluate the tooth form of the gear after it leaves the die. It is equally important to remove all the scale on the teeth before the part is placed in the nest for machining. The non-clean surface would prohibit the part from resting on the true pitch line, and thus, cause errors in machining the bore and back face of the tooth form. As a result, "runout" will occur and that will hinder the ability to "clean up" the teeth during final finish machining. All these aspects were considered prior to machining the reference surfaces.

Finish Machining of Forged Gears

The finish machining of the forged gears was necessary to center (or qualify) the back face and the bore of the gear in relation to the forged teeth. This procedure is completely opposite to the sequence of operations, used in conventional machining of gears, where a gear blank with a qualified bore is used to cut the gear teeth. The finish machining of the back face and the bore of forged gears present special problems that must be considered in production of gears by net or near-net forging.

Nest Design

The forged part was first cleaned after forging to remove scale, especially at the teeth. A nesting fixture was designed to hold the part during the subsequent turning operations. The nest, shown in Figure C-1, worked as a positive locating work-holding device. The forging was placed in the nest, resting on the pitchline, as shown in Figure C-2. The part was clamped on the back face near the outer diameter. The bore and back face were machined after clamping, as seen in Figure C-3. From this machined and qualified bore, the part is clamped from the turned back face through the bore, as seen in Figure C-4. The outside clamps are removed, permitting the remaining portion of the back face and the outer diameter to be turned, Figure C-5. The forging is not removed from the nest during the entire machining operation, thereby maintaining the positive location on the pitchline. This assures that all reference surfaces have the same orientation and location with relation to the forged teeth.

Finish Machining of Gears from the Second Series of Trials

After machining the bore and back face of the forged gears from Trials II, they were put into a #28 Gleason gear cutter to finish machining the teeth of the gear (by removing the machining allowance). The gear cutting operation was very successful in producing the desired finish tooth form from the forged parts. The cut teeth were to the designed tooth thickness. The spiral angle, with both flanks of the entire tooth form, was completely machined after a single gear cutting operation. These gear cutting results verify that the CAD phase of this program was accurate in predicting the machine settings used to produce the EDM electrode, made to manufacture the die. A forged gear, with the teeth being finish machined, is shown in Figure C-6.

After the gears forged in the second series of trials were finish machined, a pinion was cut to match the tooth form on the gear. This is necessary to compensate for any variations in the gear tooth form as compared to the master set of gears. When the gear and pinion were rolled on a gear tester, an acceptable contact pattern was produced. This contact pattern is shown in Figure C-7.

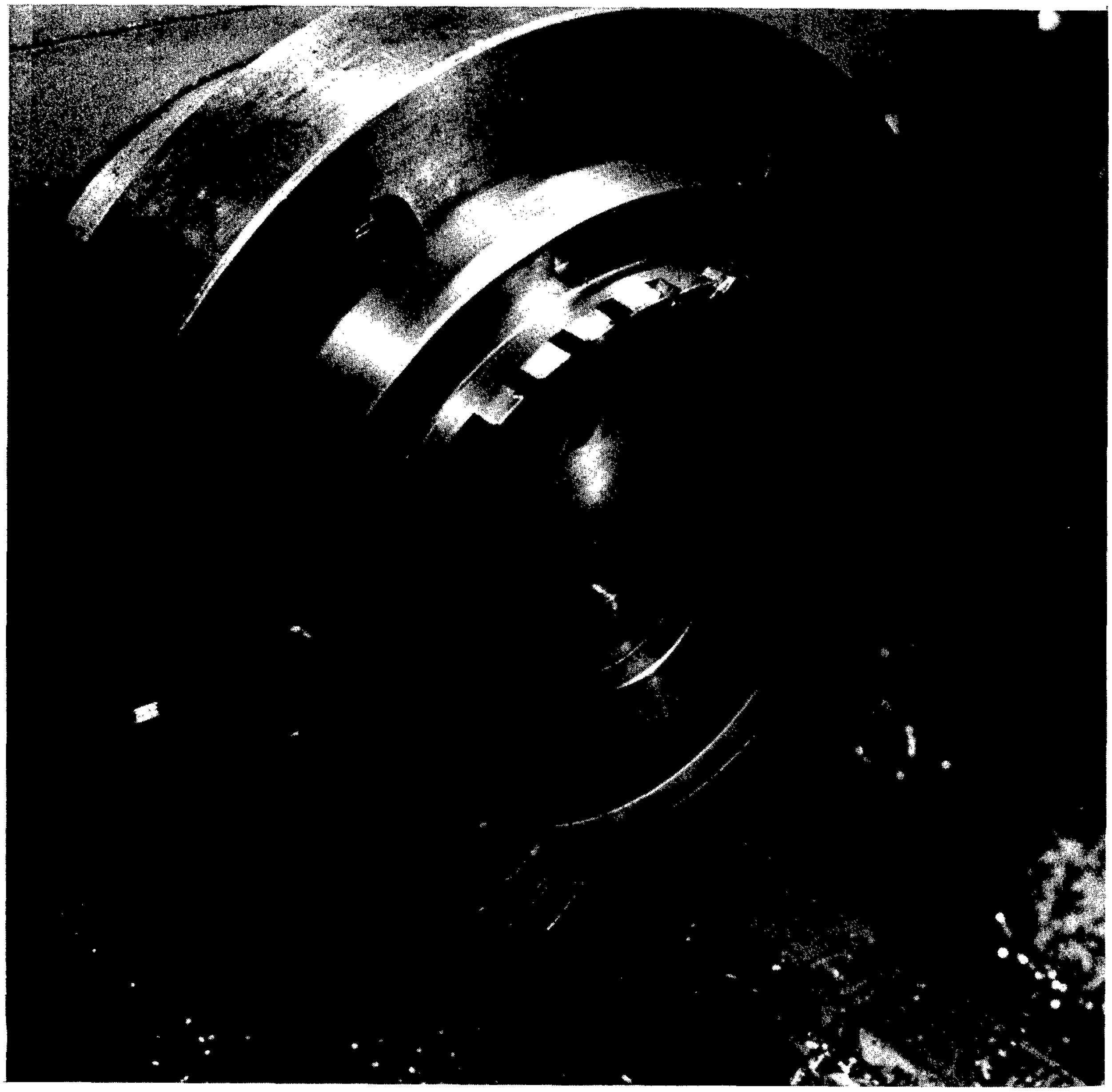


FIGURE C-1. Nesting Fixture

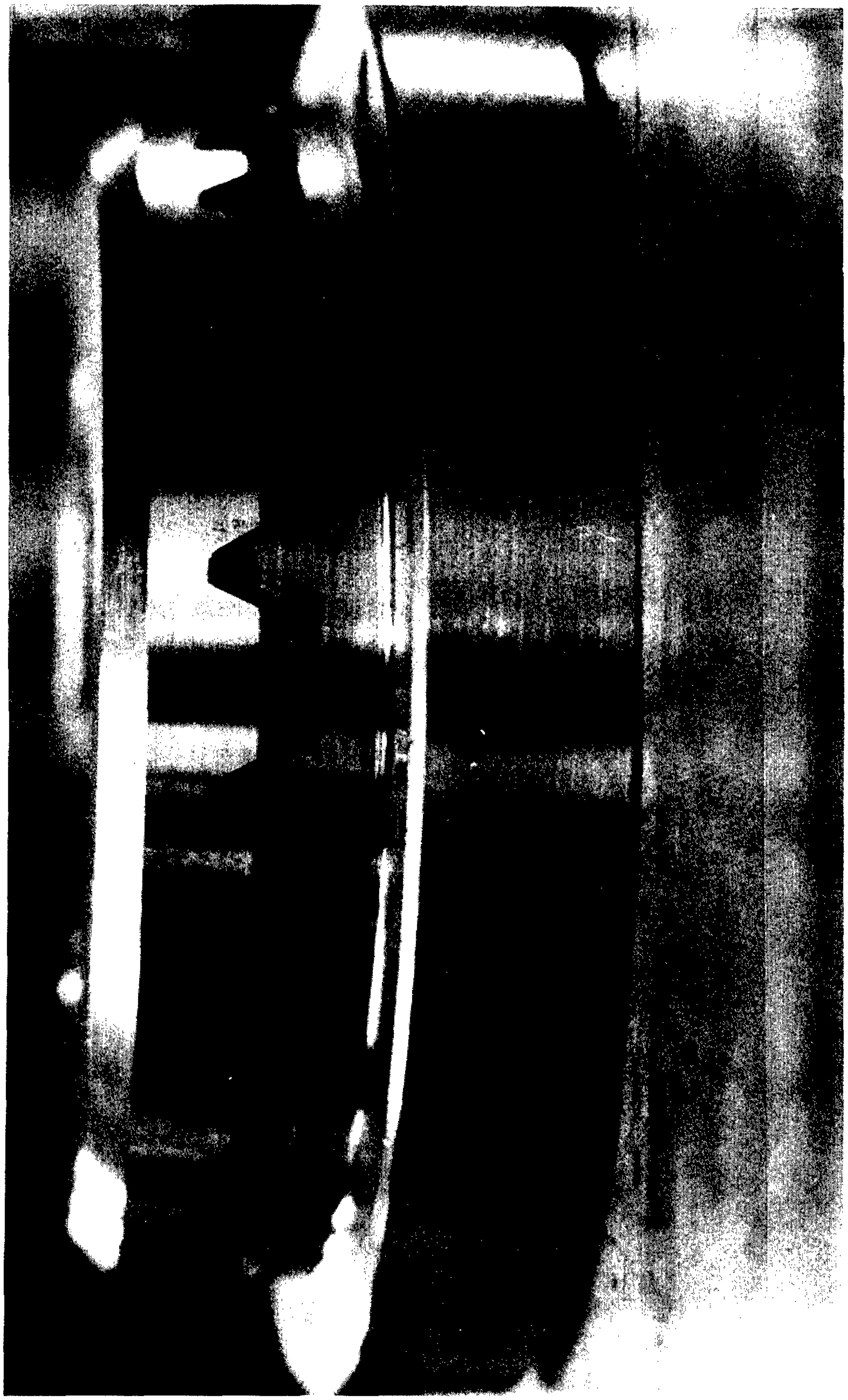


FIGURE C-2. Forged Gear Resting on its Pitchline. Upper Part is Gear, Lower Part is Nest.

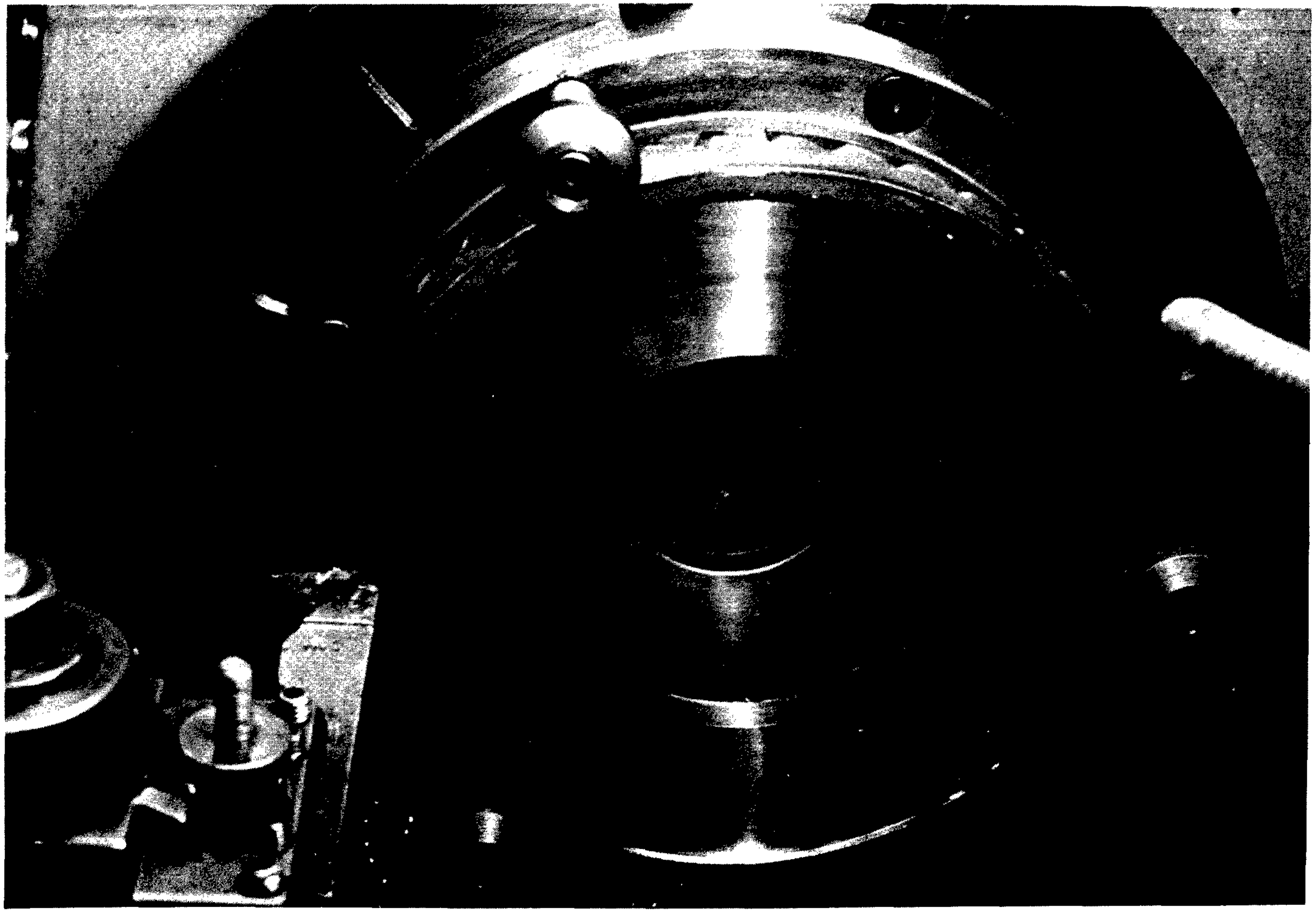


FIGURE C-3. Back Face of Forged Gear While Being Machined

FIGURE C-4. Forged Gear Clamped on the Back Face Through the Bore

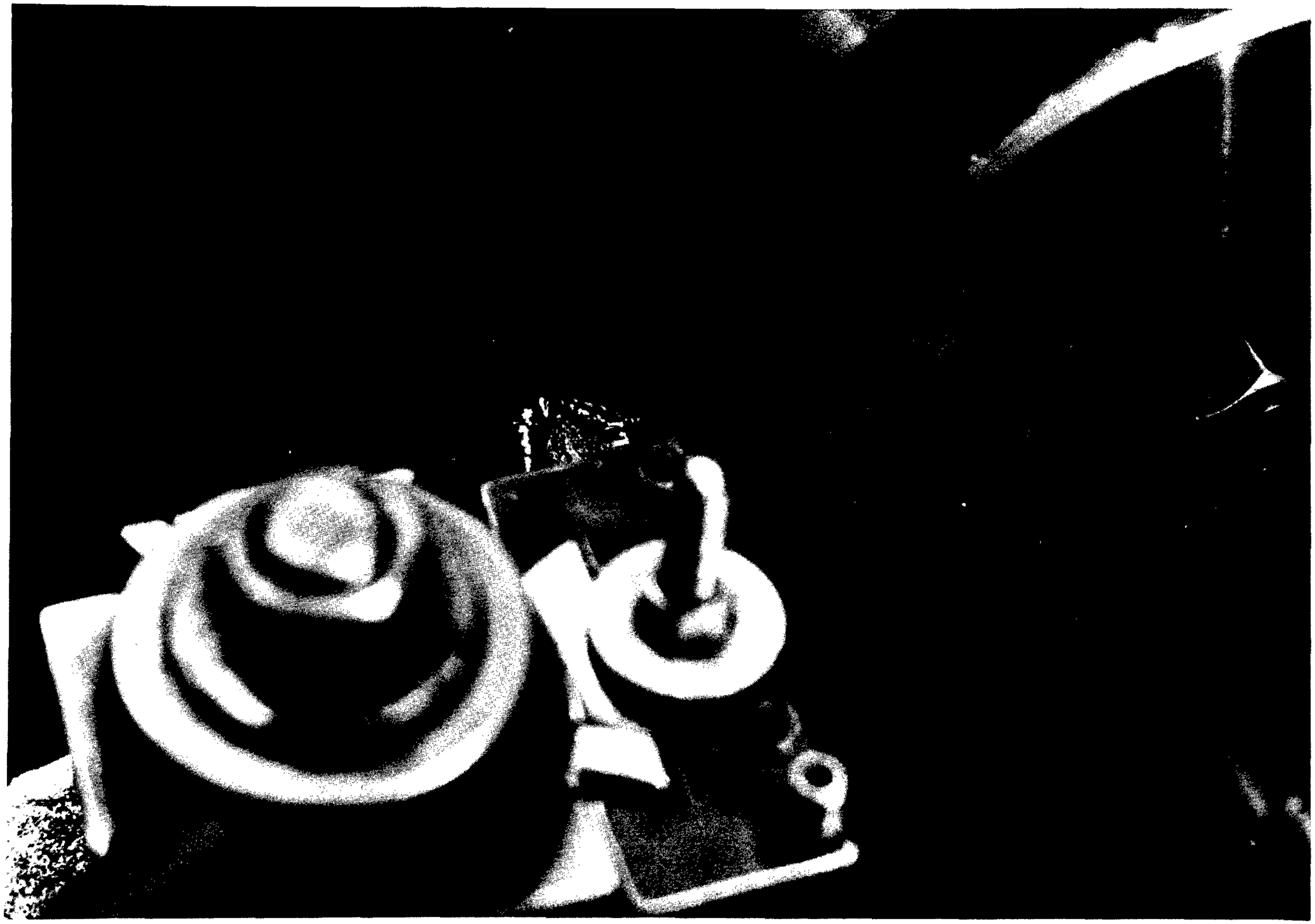


FIGURE C-5. The Outer Diameter of the Forged Gear During the Turning Operation

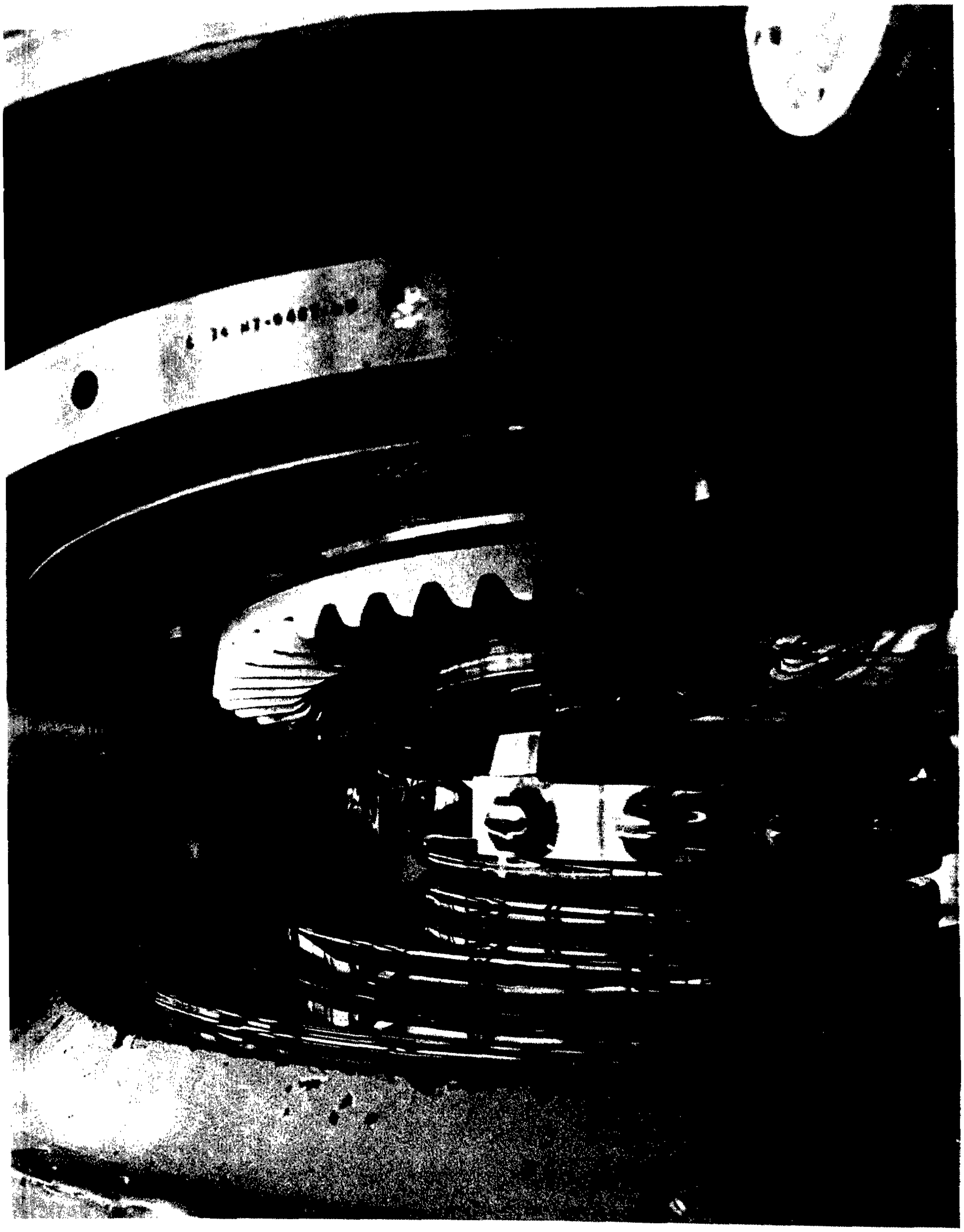


FIGURE C-6. Forged Gear (From the Second Series of Forging Trials) With Teeth Being Finish Machined on a Gleason Gear Generator

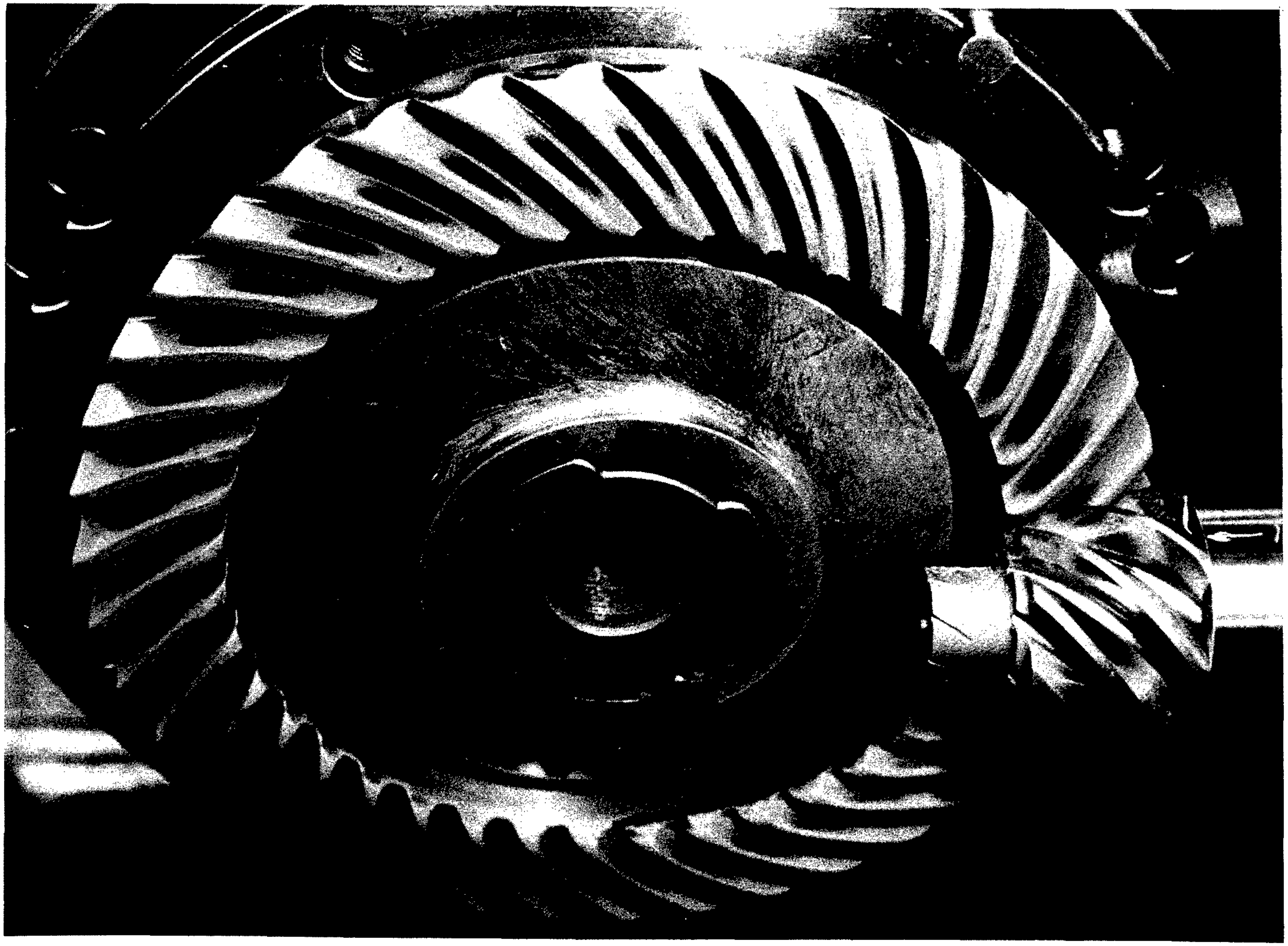


FIGURE C-7. Contact Pattern (of Finish Machined Near-Net Forged Gear) Shown by Dark Areas at Tooth Surfaces

Finish Machining of Gears from the Third Series of Trials

The gears with net forged teeth, from Trials III, were designed without any machining stock on the teeth. The only machining required was on the reference surfaces, namely, the bore and back face of the gear. This machining procedure was the same as that used for machining the bore and the back face of the gears forged in Trials II. After the net forged gears were machined, it was again necessary to cut a pinion to match the tooth form of the gear. The pinion was cut and rolled against the forged gear teeth producing an acceptable contact patter. This contact pattern is shown in Figure C-8.

FORGING INSPECTION

The forgings were inspected for the following characteristics before they were machined:

A. Thru Bore Thickness - This is the thickness of the center flange from the back face to the front face. This dimension is shown in Figure C-9. The thickness was measured with micrometers.

B. Degree of Fill - The tooth fill was measured radially along the top of the gear tooth. This value reflects the length of the tooth tip in contact with the die. See Figures C-9 and B-3. The percentage of fill is calculated by dividing the measured top tooth length by the designed tooth length of 1.915 inches (48.64 mm).

C. Chordal Thickness - The chordal thickness is the length of the chord subtending a circular tooth thickness arc, as shown in Figure C-10. The chordal addendum was also measured. The chordal addendum is the height from the top of the tooth to the chord subtending the circular-thickness, as shown in

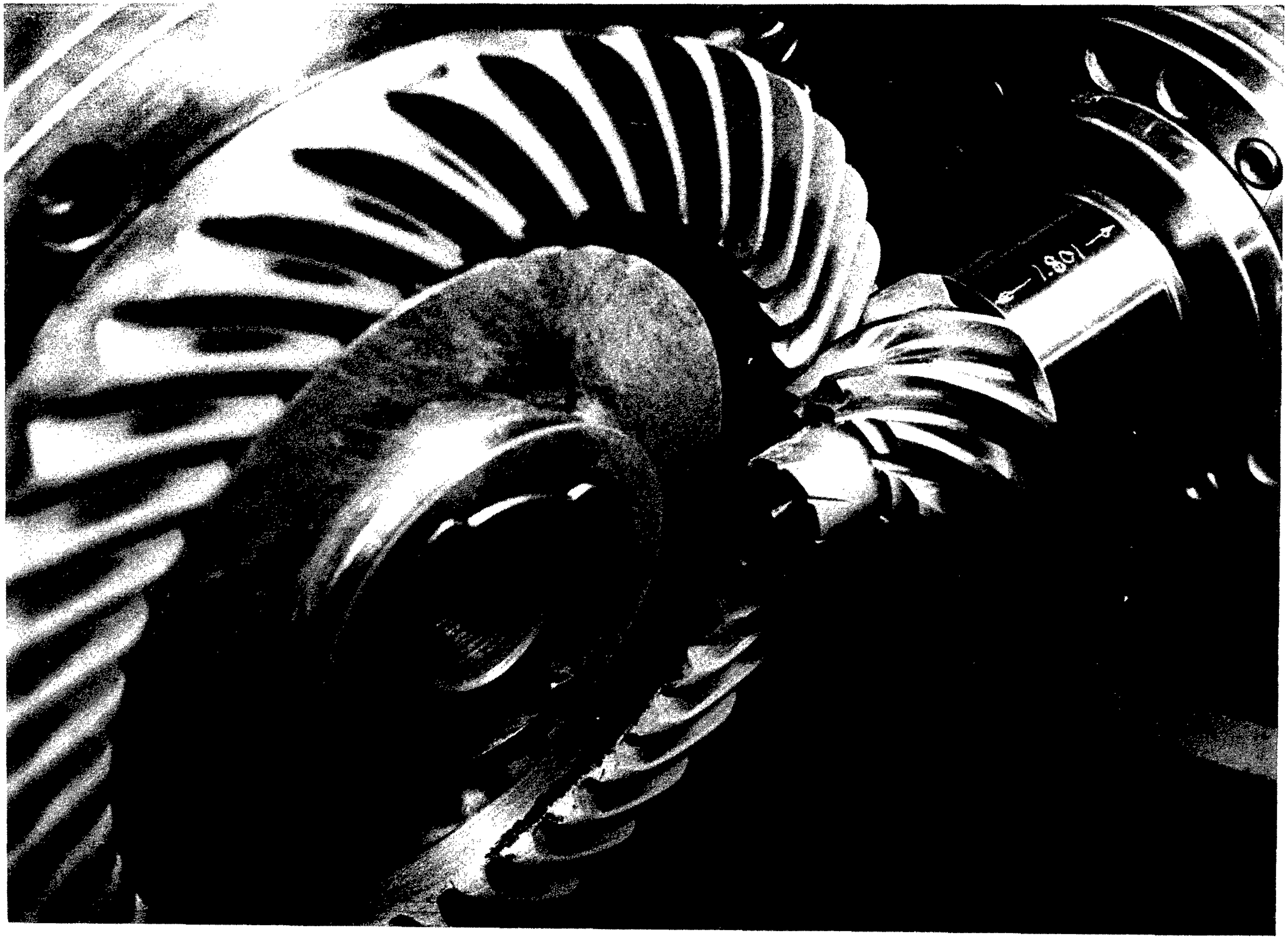


FIGURE C-8. Tooth Contact Pattern of Net Forged Gear (From the Third Series of Trials) and Machined Matching Pinion

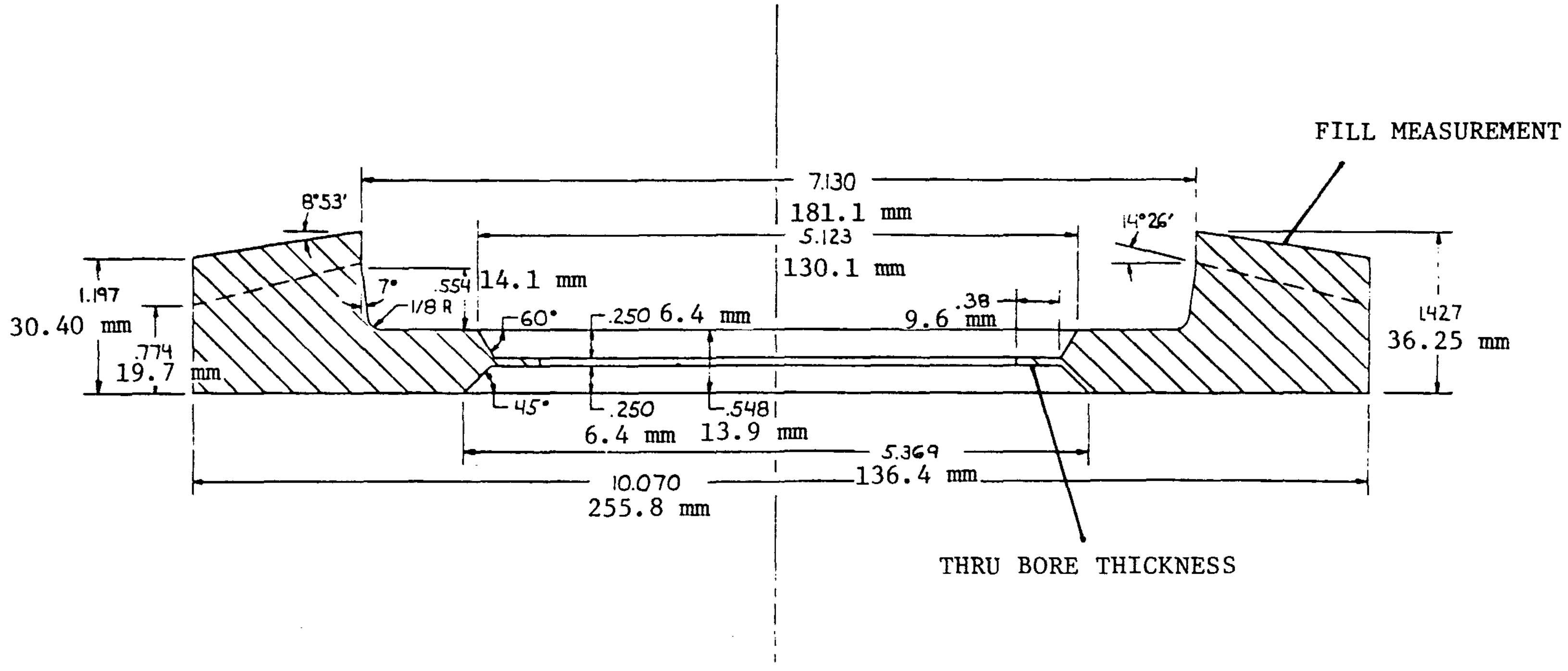


FIGURE C-9. Dimensions of Forged Spiral Bevel Gears

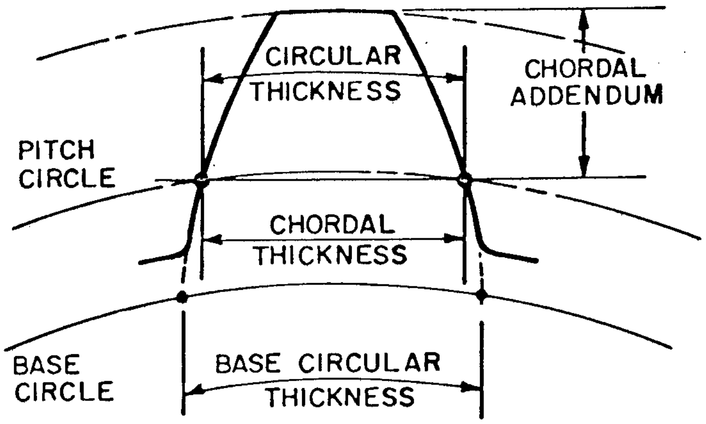


FIGURE C-10. Definition of Chordal Thickness and Chordal Addendum

Figure C-10. The addendum used from the gear tooth specifications was .058 inch (1.47 mm). The chordal thickness was measured with chordal micrometers which measure the tooth thickness at the specified addendum.

DIMENSIONAL MEASUREMENTS ON THE FORGED GEARS

Before performing any dimensional measurements on the forged gears, they were "glass beaded" to remove the scale and clean the surfaces. The gears were then checked for dimensional accuracy on the "Zeiss" coordinate measuring machine (manufactured by Carl Zeiss, D-7082 Oberkochen, West Germany). The Zeiss machine is a numerically controlled coordinate measuring machine, used for precision measurements of gear tooth surfaces. As shown in Figure C-11, the gear is clamped on the machine table representing the X-slide. The column carries the probe head, shown in Figure C-12, and is mobile in Y-direction. The probe head itself moves in the Z-direction. Measuring spiral bevel gears on the Zeiss multi-coordinate measuring machine offers many advantages over conventional gear measuring devices in terms of the recording of measured values, reduced uncertainity of measuremnts, convenience of operation, and the degree of automation. In contrast to conventional gear measuring techniques, multicoordinate measuring machines use no mechanical transfer elements for coupling the rotational and translational movements. All the necessary movement sequences for tracing involute or tooth angle are embodied digitally with high resolution (0.2 or 0.5 μm) and are related to each other by the computer. Measurements of pitch take place with the computer-controlled rotary indexing table, as shown in Figure C-11, which is completely integrated into the machine function. Its resolution is 0.5 seconds of arc at a measuring uncertainty of 1 second of arc.

To evaluate the dimensions of the forged spiral bevel gears using the Zeiss machine, it is necessary to first measure a cut master gear and store the measured coordinates in the computer memory. The forged and cleaned gear is then measured and its coordinates are automatically compared to the nominal reference points of the master cut gear. The results (differences between the gear and master) are then plotted in a graphical form. Figure

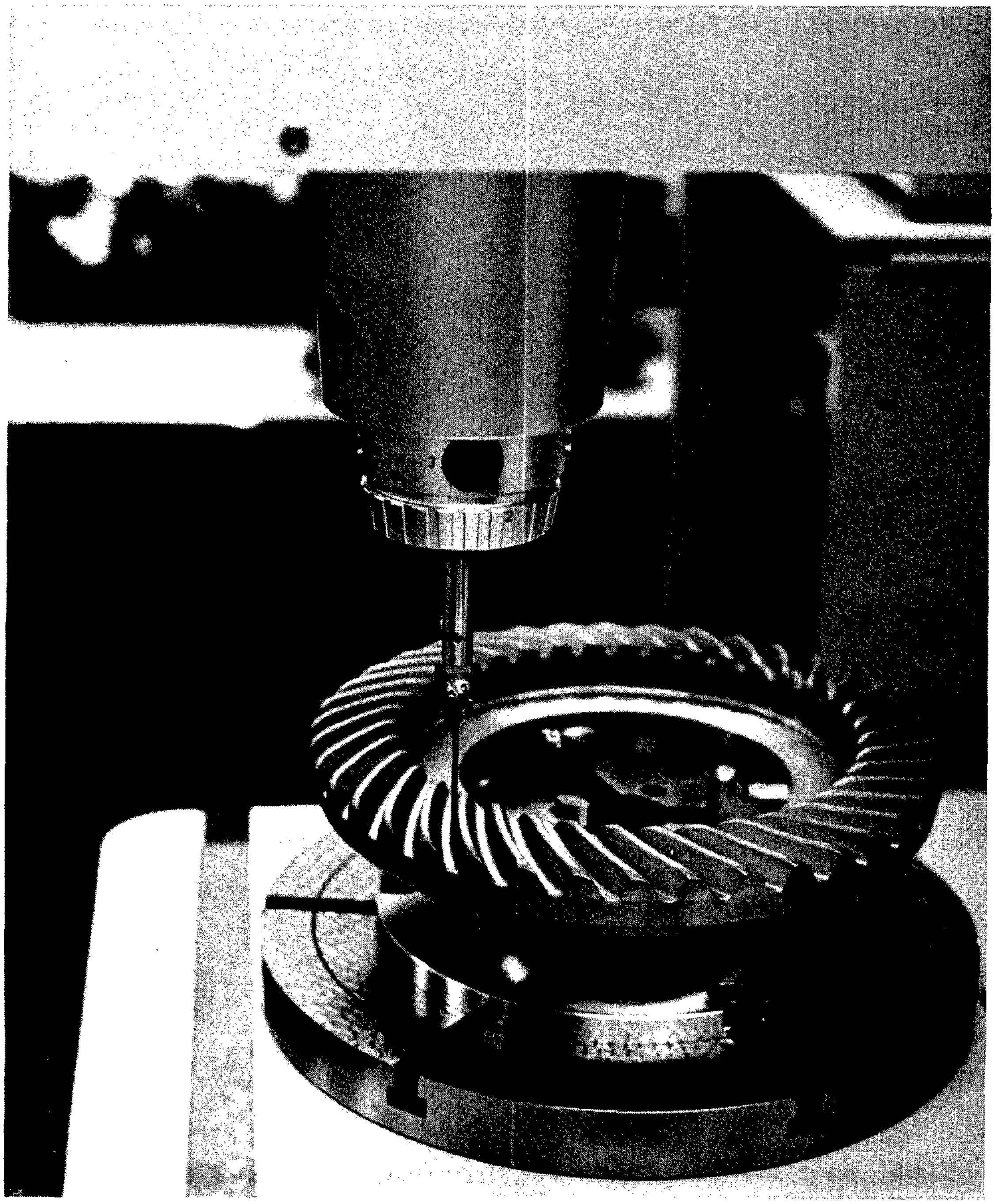


FIGURE C-11. Gear Clamped on the Computer-Controlled Rotary Table of the Zeiss Machine

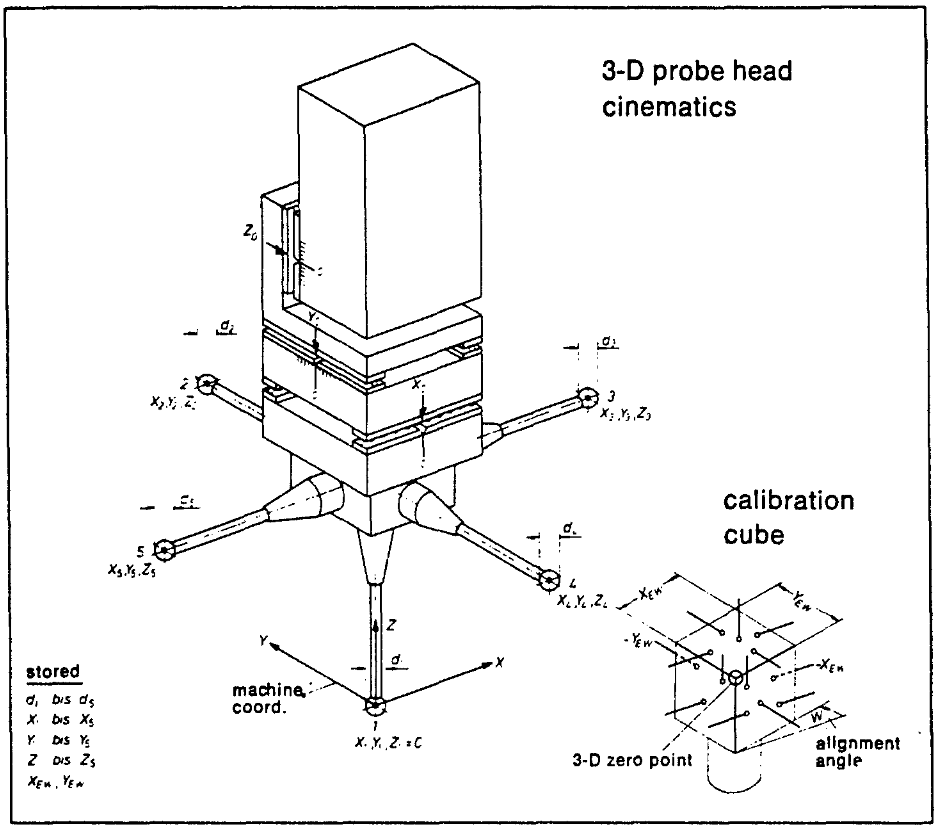


FIGURE C-12. The Zeiss Automatic 3-D Probe Head

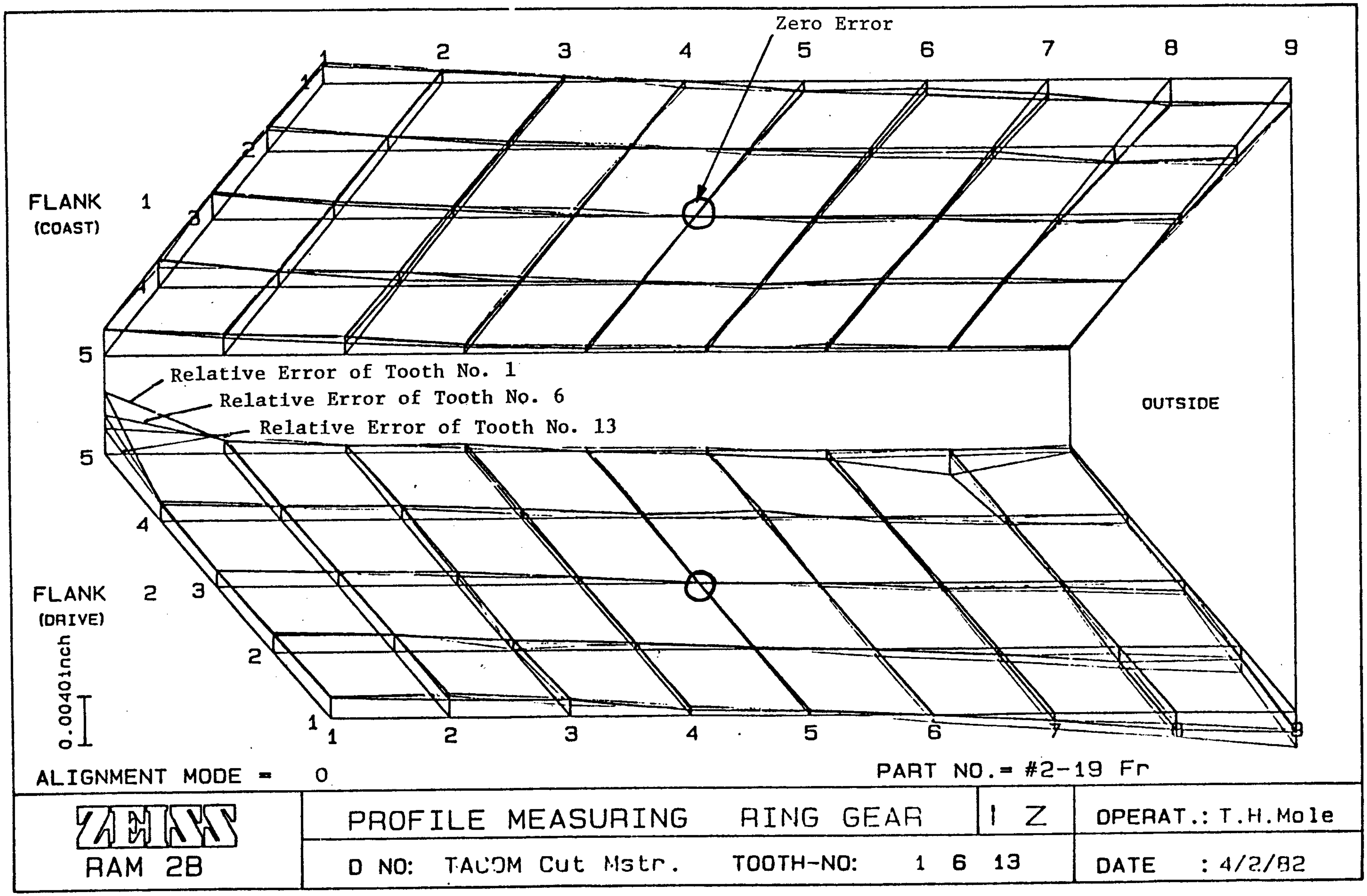


FIGURE C-13a. Zeiss Gear Tooth Plots, Graphically Illustrating the Tooth Form Variation of Forged Gears Versus the Cut Master Gear

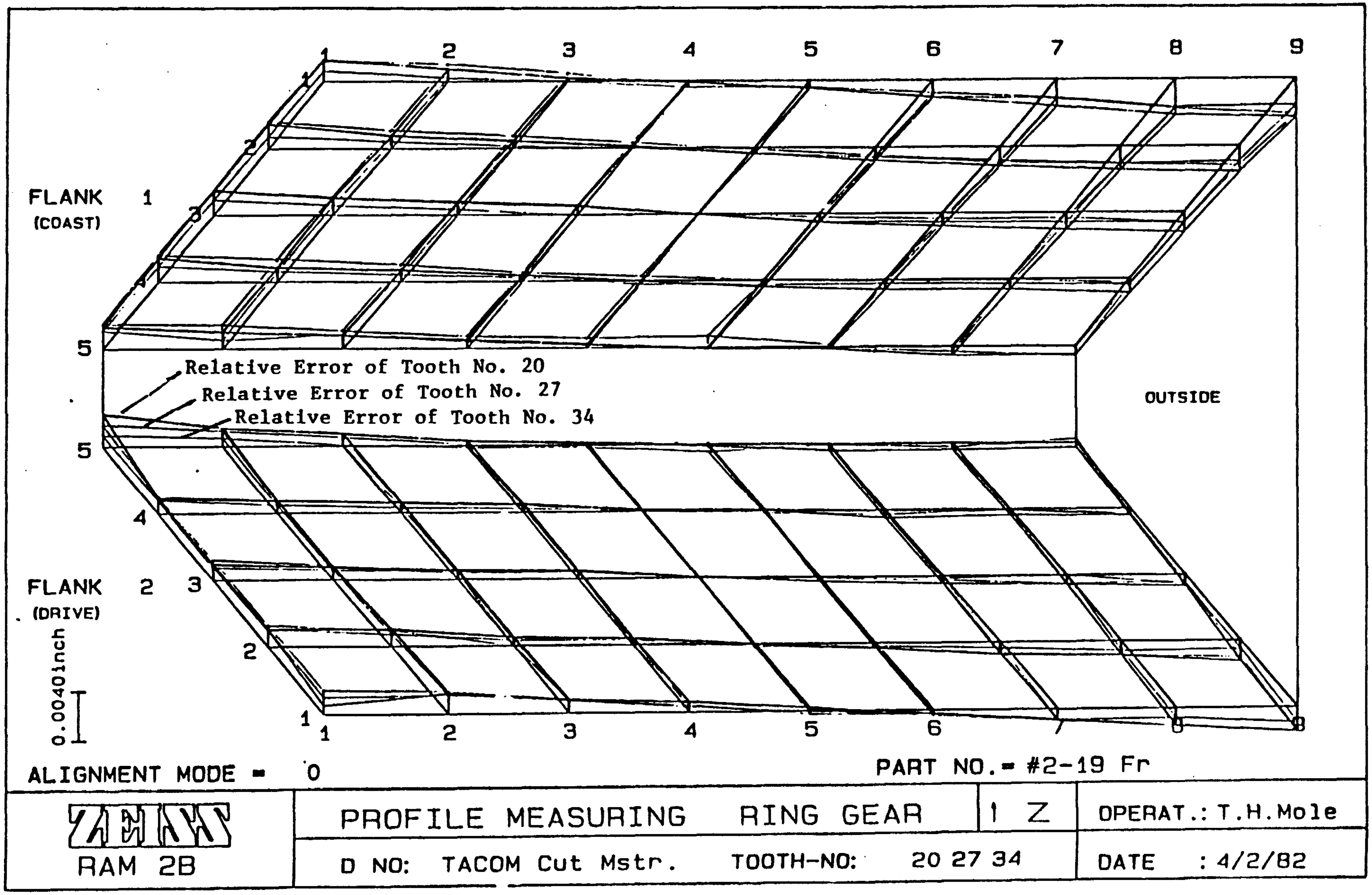


FIGURE C-13b. (Continued)

C-13 shows the plot of the profile of six teeth that were measured (teeth Nos. 1, 6 and 13 are shown in Figure C-13a; teeth Nos. 20, 27 and 34 are shown in Figure C-13b). The plots, shown in Figure C-13, show the relative deviation of the forged tooth profile from a master gear tooth produced by conventional cutting (using a Gleason generator). Note that the relative error at the center of the profile is zero, i.e., the variations were measured relative to the center of the coast and drive surfaces of the master gear. The scale of the relative error is shown at the left side of Figure C-13. Figure C-14 shows a 3-D representation of the profile measurements. The plots of Figure C-13 show that the net forged gear tooth is an excellent reproduction of the master gear tooth form with a maximum variation of 0.003 inches (0.0762 mm). This minor difference can be easily compensated for, during the cutting of the mating pinion.

Another form of output from the Zeiss machine is shown in Figure C-15. This plot explains both the index variation and the pitch variation. As shown in Figure C-11, the probe is placed between the first and 39th tooth (forged gear has 39 teeth). It measures a point at the same height and radius from the center to every tooth on the gear. The pitch variation is measured to determine the differences in spacing between each two consecutive teeth. The index variation is the cumulative variation of the differences in spacing between the first tooth and the consecutive teeth.

The results of the Zeiss machine measurements can also be presented in tabular form as shown in Table C-1 and C-2. In Table C-1, X,Y, and Z represent the X,Y, and Z coordinates of points on the tooth surface measured relative to the gear (workpiece) coordinate system. Figure C-16 illustrates the machine coordinate system which is indicated with X_M, Y_M and Z_M, and the workpiece coordinate system designated with X_W, Y_W and Z_W. The exact position of the workpiece coordinate system is defined by probing a number of surface points. In the example shown in Figure C-16, the surface normal is measured with three points. Thus, the direction of axis Z_W is also defined. Two additional points define the direction of X_W. Then another set of three points define the origin of the workpiece coordinate system. Now the workpiece is mathematically aligned, and all points to be measured will be referred to the known workpiece coordinate system. So, in Table C-1, DX, DY and DZ are the deviations of the measured point (on the forged gear)

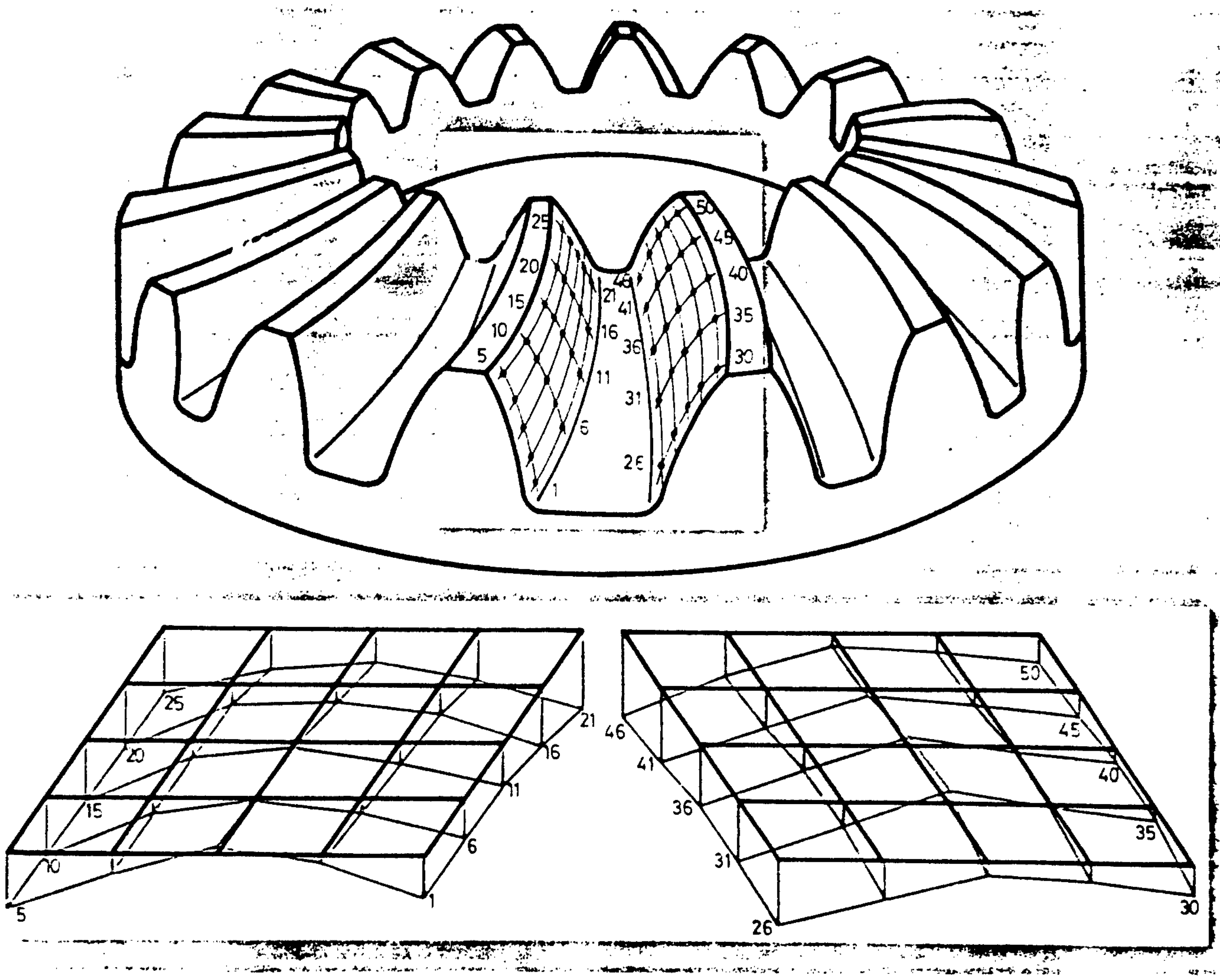
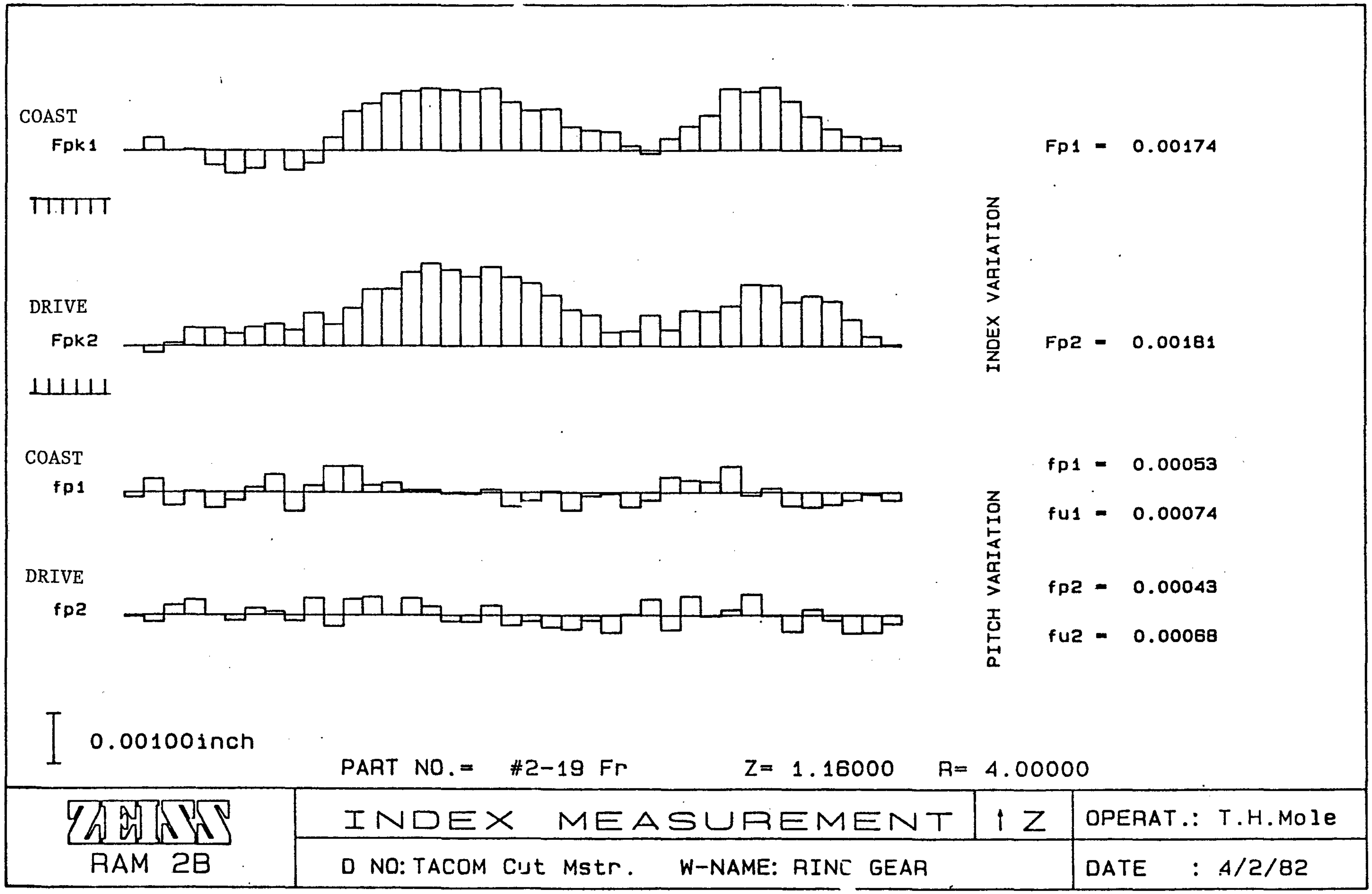


FIGURE C-14. Three-Dimensional Representation of Gear Tooth Profile Measurements



Fp1 = 0.00174

Fp2 = 0.00181

fp1 = 0.00053

fu1 = 0.00074

fp2 = 0.00043

fu2 = 0.00068

PART NO.= #2-19 Fr Z= 1.16000 R= 4.00000

OPERAT.: T.H.Mole

D NO: TACOM Cut Mstr. W-NAME: RINC GEAR

DATE : 4/2/82

FIGURE C-15. Index and Pitch Variations of Forged Gear

```
===============================================================================

                          MEASURE RECORD    ZEISS RAM 2B
Battelle Gear
=========================================

DRAWING NO          I PART NO I  ORDER NO        ISUPPLIER/CUSTOMERI OPERATION
TACOM Cut Mstr.     I #2-19 Fri 46795 Zeiss      I Eaton Gr Dev LabI Comparison

OPERATOR            I DATE
T.H.Mole            I 4/2/82
===============================================================================
 C I L I      X      I     Y     I   Z         I     DX    I   DY    I   DZ    I     EN
===============================================================================
ALIGNMENT  MODE     0
TOOTH  1          FLANK     1
    1  1     3.64467  -0.42224    1.15400     -0.00094  0.00168 -0.00001       0.00175
    1  2     3.66528  -0.43149    1.19325     -0.00089  0.00159  0.00000       0.00166
    1  3     3.68638  -0.43948    1.23176     -0.00111  0.00197  0.00000       0.00205
    1  4     3.70790  -0.44851    1.27114     -0.00087  0.00157 -0.00001       0.00164
    1  5     3.72930  -0.45622    1.30999     -0.00113  0.00204  0.00000       0.00213


    2  1     3.80810  -0.31577    1.11497     -0.00055  0.00106  0.00000       0.00109
    2  2     3.82557  -0.32812    1.15784     -0.00064  0.00116 -0.00000       0.00120
    2  3     3.84275  -0.34050    1.20061     -0.00077  0.00137  0.00001       0.00144
    2  4     3.86032  -0.35305    1.24377     -0.00077  0.00136  0.00001       0.00142
    2  5     3.87757  -0.36525    1.28662     -0.00095  0.00166 -0.00000       0.00174


    3  1     3.96850  -0.20020    1.07541     -0.00028  0.00048 -0.00001       0.00050
    3  2     3.98233  -0.21711    1.12233     -0.00037  0.00066  0.00000       0.00069
    3  3     3.99569  -0.23436    1.16943     -0.00050  0.00086 -0.00001       0.00090
    3  4     4.00927  -0.25126    1.21637     -0.00062  0.00111  0.00000       0.00116
    3  5     4.02280  -0.26834    1.26343     -0.00072  0.00126 -0.00001       0.00131


    4  1     4.12469  -0.07632    1.03579      0.00001  0.00004  0.00000       0.00002
    4  2     4.13379  -0.09874    1.08612     -0.00022  0.00037  0.00001       0.00039
    4  3     4.14486  -0.12059    1.13791     -0.00036  0.00066  0.00000       0.00068
    4  4     4.15495  -0.14294    1.18893     -0.00038  0.00067  0.00000       0.00069
    4  5     4.16502  -0.16527    1.24015     -0.00040  0.00073 -0.00001       0.00075


    5  1     4.27647   0.05550    0.99606      0.00048 -0.00085  0.00001      -0.00087
    5  2     4.28354   0.02798    1.05111      0.00013 -0.00025 -0.00000      -0.00025
    5  3     4.29049   0.00000    1.10642     -0.00001 -0.00002 -0.00000      -0.00001
    5  4     4.29737  -0.02778    1.16165     -0.00011  0.00019  0.00001       0.00020
    5  5     4.30407  -0.05543    1.21690     -0.00031  0.00055 -0.00000       0.00057


    6  1     4.42428   0.19702    0.95638      0.00072 -0.00125 -0.00001      -0.00127
    6  2     4.42625   0.16270    1.01579      0.00044 -0.00081  0.00000      -0.00081
    6  3     4.43230   0.12843    1.07500      0.00027 -0.00048 -0.00001      -0.00048
    6  4     4.43627   0.09451    1.13482      0.00005 -0.00010  0.00000      -0.00010
    6  5     4.43988   0.06111    1.19370     -0.00031  0.00052  0.00000       0.00054


    7  1     4.56721   0.34746    0.91693      0.00097 -0.00171  0.00001      -0.00170
    7  2     4.56892   0.30668    0.98024      0.00051 -0.00087  0.00001      -0.00088
    7  3     4.57041   0.26543    1.04380      0.00028 -0.00053  0.00001      -0.00052




===============================================================================
 C I L I      X      I     Y     I   Z         I     DX    I   DY    I   DZ    I     EN
===============================================================================
    7  4     4.57148   0.22461    1.10705      0.00005 -0.00009  0.00000      -0.00009
    7  5     4.57259   0.18383    1.17046     -0.00004  0.00009  0.00000       0.00009


    8  1     4.70555   0.50816    0.87744      0.00112 -0.00197 -0.00001      -0.00194
    8  2     4.70489   0.45877    0.94479      0.00081 -0.00147  0.00000      -0.00143
    8  3     4.70425   0.41061    1.01236      0.00033 -0.00057 -0.00001      -0.00057
    8  4     4.70315   0.36241    1.07970      0.00004 -0.00006  0.00001      -0.00007
    8  5     4.70181   0.31438    1.14756     -0.00015  0.00027  0.00001       0.00027


    9  1     4.83869   0.67962    0.83772      0.00116 -0.00205  0.00000      -0.00196
    9  2     4.83665   0.62217    0.90950      0.00068 -0.00118  0.00001      -0.00114
    9  3     4.83390   0.56437    0.98098      0.00049 -0.00087 -0.00000      -0.00085
    9  4     4.83079   0.50840    1.05241     -0.00004  0.00008  0.00000       0.00007
    9  5     4.82740   0.45209    1.12392     -0.00018  0.00030 -0.00001       0.00030
```

TABLE C-1. Tooth Profile Measurements in Tabular Form

```
TOOTH  1              FLANK    2
   1  1     3.62258  -0.52922    1.10975      -0.00105  0.00157 -0.00000      -0.00181
   1  2     3.67875  -0.47754    1.16191      -0.00097  0.00146 -0.00000      -0.00170
   1  3     3.73204  -0.42743    1.21275      -0.00071  0.00121  0.00000      -0.00136
   1  4     3.78545  -0.37595    1.26356      -0.00072  0.00120 -0.00001      -0.00136
   1  5     3.83818  -0.32300    1.31473      -0.00117  0.00185  0.00000      -0.00212


   2  1     3.79529  -0.42632    1.07621      -0.00116  0.00171 -0.00001      -0.00201
   2  2     3.84053  -0.37863    1.13063      -0.00079  0.00130 -0.00000      -0.00147
   2  3     3.88553  -0.32997    1.18549      -0.00073  0.00118  0.00000      -0.00134
   2  4     3.93047  -0.28096    1.24013      -0.00053  0.00086  0.00001      -0.00098
   2  5     3.97457  -0.23064    1.29509      -0.00078  0.00131 -0.00001      -0.00147


   3  1     3.96122  -0.31846    1.04082      -0.00086  0.00132 -0.00000      -0.00152
   3  2     3.99837  -0.27330    1.09910      -0.00036  0.00062  0.00001      -0.00069
   3  3     4.03528  -0.22669    1.15809      -0.00041  0.00067 -0.00000      -0.00076
   3  4     4.07185  -0.17990    1.21661      -0.00043  0.00072  0.00000      -0.00081
   3  5     4.10824  -0.13286    1.27545      -0.00038  0.00060  0.00000      -0.00069


   4  1     4.12282  -0.20307    1.00587      -0.00045  0.00066 -0.00002      -0.00078
   4  2     4.15200  -0.16035    1.06787      -0.00019  0.00031 -0.00001      -0.00035
   4  3     4.18098  -0.11670    1.13087      -0.00030  0.00046 -0.00001      -0.00053
   4  4     4.20998  -0.07288    1.19285      -0.00026  0.00040  0.00000      -0.00046
   4  5     4.23866  -0.02907    1.25532      -0.00024  0.00037  0.00000      -0.00042


   5  1     4.27980  -0.07915    0.97072      -0.00027  0.00044 -0.00001      -0.00050
   5  2     4.30161  -0.03950    1.03674      -0.00018  0.00026  0.00001      -0.00030
   5  3     4.32315   0.00009    1.10308      -0.00002  0.00004  0.00001      -0.00004
   5  4     4.34458   0.04068    1.16940      -0.00025  0.00037 -0.00000      -0.00043
   5  5     4.36590   0.08050    1.23562      -0.00015  0.00024 -0.00000      -0.00027


   6  1     4.43258   0.05266    0.93554       0.00005 -0.00012 -0.00001       0.00012
   6  2     4.44672   0.08825    1.00568       0.00003 -0.00003 -0.00001       0.00004



================================================================================
 C I L I       X      I      Y     I    Z        I     DX    I    DY    I   DZ     I     EN
================================================================================
   6  3     4.46124   0.12408    1.07600       0.00001  0.00001 -0.00001      -0.00001
   6  4     4.47551   0.16009    1.14595      -0.00013  0.00020  0.00000      -0.00023
   6  5     4.48965   0.19593    1.21613      -0.00012  0.00021 -0.00001      -0.00023


   7  1     4.57997   0.19250    0.90041       0.00033 -0.00050 -0.00000       0.00057
   7  2     4.58764   0.22341    0.97409       0.00036 -0.00054  0.00000       0.00062
   7  3     4.59542   0.25491    1.04809       0.00018 -0.00028  0.00001       0.00032
   7  4     4.60283   0.28595    1.12203       0.00009 -0.00014 -0.00001       0.00015
   7  5     4.61025   0.31668    1.19618       0.00013 -0.00019  0.00001       0.00022


   8  1     4.72272   0.34106    0.86551       0.00058 -0.00086 -0.00002       0.00097
   8  2     4.72405   0.36743    0.94277       0.00034 -0.00051  0.00002       0.00058
   8  3     4.72512   0.39333    1.02083       0.00016 -0.00026  0.00001       0.00029
   8  4     4.72625   0.41889    1.09858       0.00013 -0.00019 -0.00000       0.00022
   8  5     4.72737   0.44446    1.17628       0.00008 -0.00011  0.00000       0.00013


   9  1     4.86065   0.49875    0.83018       0.00088 -0.00134 -0.00002       0.00148
   9  2     4.85582   0.51916    0.91179       0.00056 -0.00084  0.00001       0.00094
   9  3     4.85084   0.53990    0.99339       0.00007 -0.00010 -0.00001       0.00011
   9  4     4.84573   0.55935    1.07496      -0.00003  0.00004 -0.00001      -0.00005
   9  5     4.84088   0.57899    1.15668      -0.00014  0.00023 -0.00000      -0.00025
```

TABLE C-1. (Continued)

```
                         INDEX MEASUREMENT RAM 2B
Battelle Gear
DRAWING NO          | PART NO |  ORDER NO        |SUPPLIER/CUSTOMER| OPERATION
TACOM Cut Mstr.     | #2-19 Fr| 46795 Zeiss      | Eaton Gr Dev Lab| Comparison

OPERATOR            | DATE
T.H.Mole            | 4/2/82
======================================================================
GAP   |POINT|      fp1    |      fp2    |      fr     |     Fpk1    |    Fpk2
======================================================================
  1              0.00000                                  0.00000
  2              0.00014                                  0.00014
  3             -0.00023                                 -0.00009
  4             -0.00001                                 -0.00011
  5             -0.00032                                 -0.00043
  6             -0.00014                                 -0.00058
  7              0.00007                                 -0.00051
  8              0.00037                                 -0.00014
  9             -0.00039                                 -0.00052
 10              0.00014                                 -0.00039
 11              0.00053                                  0.00015
 12              0.00051                                  0.00066
 13              0.00009                                  0.00074
 14              0.00026                                  0.00100
 15              0.00006                                  0.00107
 16              0.00005                                  0.00111
 17             -0.00003                                  0.00109
 18             -0.00004                                  0.00105
 19              0.00009                                  0.00114
 20             -0.00028                                  0.00086
 21             -0.00017                                  0.00069
 22              0.00004                                  0.00073
 23             -0.00038                                  0.00035
 24             -0.00007                                  0.00028
 25             -0.00003                                  0.00025
 26             -0.00028                                 -0.00003
 27             -0.00017                                 -0.00020
 28              0.00030                                  0.00010
 29              0.00026                                  0.00036
 30              0.00023                                  0.00059
 31              0.00051                                  0.00110
 32             -0.00003                                  0.00107
 33              0.00007                                  0.00114
 34             -0.00028                                  0.00086
 35             -0.00032                                  0.00054
 36             -0.00023                                  0.00031
 37             -0.00015                                  0.00016
 38             -0.00005                                  0.00011
 39             -0.00015                                 -0.00004
  1              0.00004
```

TABLE C-2. Index Measurements

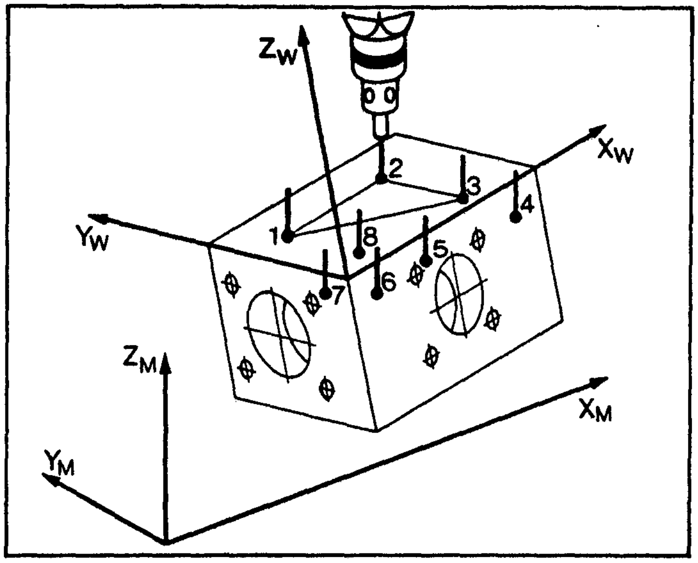


FIGURE C-16. Zeiss Machine and Workpiece Coordinate Systems from the corresponding point on the nominal master gear manufactured by cutting on a Gleason machine (generator). Now, if the unit vectors in the directions of the workpiece (forged gear) axis are NX, NY and NZ, EN in Table C-1 can be represented as:

$$EN = NX \cdot DX + NY \cdot DY + NZ \cdot DZ \quad .$$

EN expresses the flank form deviation in the direction of the normal vector.

Table C-2 shows the numerical values of the pitch variations (fpl) and the index variation (Fpkl). Both are discussed and represented graphically in Figure C-15. The Zeiss measurements form a complete picture of the teeth of the gear. The profile measurements (Figure C-13 and Table C-1) show the tooth form variation, and the index measurements (Figure C-15 and Table C-2) show the tooth spacing variation.

The results of the Zeiss measurements confirmed the accuracy of the CAD/CAM system developed in this project. These results, for the three sets of forging trials, are summarized in Tables C-3, C-4 and C-5.

TABLE C-3. Forging Trials Conducted September 14, 1981, at Eaton Corporation, Forge Division, Marion, Ohio

Billet Coating: Graphite Products GP-158 Atmosphere in Furnace: Nitrogen

Lubricant: Pro Chem TC 7955 B Die Temperature: 300° F (149° C)

Trial Number	Billet Temp. °F	Billet Temp. °C	Forging Load tons	Forging Load 1000 kg	Flange Thickness in[1]	Flange Thickness mm	Heating Time min	Tooth Fill[2] in	Tooth Fill[2] mm	Tooth Fill[2] pct[3]	Comments
1-1	1,893	1,034	392	356	0.960	24.38	30	--	--	--	Little fill on the teeth
1-2	--	--	--	--	--	--	45	--	--	--	Not forged
1-3	1,882	1,028	1,057	959	0.732	18.59	30	--	--	--	Shim added and fill improved
1-4	1,921	1,049	1,868	1,695	0.625	15.87	30	1.150	29.20	60	Nitrogen flow increased, more shim, better fill
1-5	1,913	1,045	2,881	2,614	0.608	15.44	20	1.380	35.05	72	More shim and best fill yet
1-6	1,915	1,046	2,873	2,606	--	--	40	--	--	--	
1-7	1,928	1,053	2,864	2,598	0.610	15.49	40	1.095	27.81	57	
1-8	1,941	1,061	2,858	2,593	0.606	15.39	40	1.240	31.50	65	
1-9	1,908	1,042	2,738	2,484	0.605	15.37	40	1.300	33.02	68	
1-10	1,936	1,058	2,665	2,418	0.608	15.44	30	1.360	34.54	71	
1-11	1,942	1,061	2,620	2,377	0.618	15.70	30	1.270	32.26	66	Lowest amount of scale
1-12	1,920	1,049	2,660	2,413	0.621	15.77	30	1.440	36.58	75	
1-13	2,023	1,106	2,601	2,360	--	--	30	--	--	--	
1-14	1,980	1,082	2,576	2,337	0.609	15.47	20	1.330	33.78	70	
1-15	1,944	1,062	2,557	2,320	0.611	15.52	20	1.340	34.04	71	
1-16	1,974	1,079	2,543	2,307	0.615	15.62	20	1.365	34.67	75	
1-17	1,958	1,070	2,528	2,293	0.616	15.65	20	1.440	36.58	58	
1-18	1,970	1,077	2,508	2,275	0.608	15.44	20	1.120	28.45	64	
1-19	1,984	1,084	2,553	2,316	0.621	15.77	20	1.220	30.99	65	
1-20	2,024	1,107	2,491	2,260	0.611	15.52	20	1.250	31.75	76	
1-21	1,954	1,068	2,508	2,275	0.620	15.75	20	1.450	36.83	--	

[1] Average Values

[2] Tooth fill is measured radially along the tip of the gear tooth. Value reflects the amount of the tooth tip contacting the die (See Figure B-3)

[3] Percent fill is calculated by dividing fill measurement by the designed tooth length of 1.915 in (48.64 mm)

TABLE C-4. Forging Trials Conducted January 13, 1982, at Eaton Corporation Forge Division, Marion, Ohio

Billet Coating: Acheson Delta Forge 182 — Atmosphere in Induction Coil: Nitrogen

Lubricant: Acheson Delta Forge 31 — Die Temperature: 300° F (149° C)

Trial	Billet Temp.		Forging Load		Flange Thickness		Heating Time	Tooth Fill[2]			
Number	°F	°C	tons	1000 kg	in[1]	mm	min	in	mm	pct[3]	Comments
2-1	2,015	1,101	--	--	--	--	2.5	--	--	--	Did not forge
2-2	2,011	1,099	2,458	2,212	0.610	15.0	"	--	--	--	Water-cooled
2-3	2,022	1,105	2,930	2,637	0.595	14.5	"	--	--	--	
2-4	--	--	--	--	--	--	--	--	--	--	Did not forge
2-5	2,033	1,111	2,970	2,673	0.595	14.5	2.5	--	--	--	
2-6	2,015	1,101	2,906	2,615	"	"	"	--	--	--	New operator
2-7	1,998	1,092	2,892	2,602	"	"	"	1.372	34.8	71.6	
2-8	1,970	1,076	2,860	2,574	"	"	"	1.112	28.2	58.1	
2-9	2,013	1,100	2,906	2,615	"	"	"	1.415	35.9	73.9	
2-10	1,950	1,065	2,856	2,570	"	"	"	1.282	32.5	67.0	Original operator
2-11	1,998	1,092	2,836	2,552	"	"	"	1.415	35.9	73.9	Started placing flame ring in die after every piece
2-12	1,998	1,092	2,861	2,575	"	"	"	1.335	33.9	69.7	
2-13	2,015	1,101	2,856	2,570	"	"	"	1.462	37.1	76.4	
2-14	2,124	1,162	2,861	2,574	"	"	"	1.543	39.2	80.6	
2-15	2,033	1,111	2,814	2,532	"	"	"	--	--	--	Coil allowed to cool before trial
2-16	1,978	1,081	2,800	2,520	"	"	"	1.399	35.5	73.0	Temp. after forge - 1684
2-17	2,016	1,102	2,882	2,594	"	"	"	1.382	35.1	72.2	Temp. after forge - 1774
2-18	1,960	1,071	2,864	2,577	"	"	"	1.248	31.7	65.2	
2-19	2,005	1,096	2,840	2,556	"	"	"	1.345	34.1	70.2	
2-20	2,036	1,113	2,861	2,575	"	"	"	--	--	--	
2-21	2,005	1,096	2,860	2,575	"	"	"	--	--	--	
2-22	1,984	1,984	2,851	2,565	"	"	"	1.396	35.4	72.9	
2-23	2,012	1,100	2,854	2,568	"	"	"	1.365	34.6	71.3	
2-24	2,001	1,094	2,894	2,604	"	"	"	1.428	36.3	74.6	

[1] Average Values

[2] Tooth fill is measured radially along the tip of the gear tooth. Value reflects the amount of the tooth tip contacting the die (See Figure B-3)

[3] Percent fill is calculated by dividing fill measurement by the designed tooth length of 1.915 inches (48.64 mm)

TABLE C-5. Forging Trials Conducted March 15, 1982, at Eaton Corporation Forge Division, Marion, Ohio

Billet Coating: None

Atmosphere in Induction Coil: Nitrogen

Lubricant: Acheson Delta Forge 31

Die Temperature: 300° F (149° C)

Trial Number	Billet Temp.		Forging Load		Flange Thickness		Heating Time min	Tooth Fill[2]			Comments
	°F	°C	tons	1000 kg	in[1]	mm		in	mm	pct[3]	
3-1	2,000	1,093	1,201	1,080	0.621	15.77	--	0.0	0.0	0.0	Part in die wrong
3-2	"	"	1,285	1,156	0.620	15.75	--	0.0	0.0	0.0	
3-3	"	"	1,268	1,141	0.629	15.97	--	0.0	0.0	0.0	
3-4	"	"	1,661	1,494	0.666	16.91	--	.500	12.70	26.1	
3-5	"	"	2,154	1,938	--	--	--	--	--	--	
3-6	"	"	2,136	1,920	0.660	16.76	--	0.0	0.0	0.0	
3-7	"	"	2,461	2,214	0.656	16.66	--	1.415	35.94	73.9	
3-8	"	"	2,435	2,191	0.657	16.68	--	1.400	35.56	73.1	
3-9	"	"	2,393	2,153	0.656	16.66	--	1.300	33.02	68.0	
3-10	"	"	2,386	2,147	0.651	16.53	--	1.440	36.57	75.2	
3-11	"	"	2,363	2,126	0.652	16.56	--	1.425	36.19	74.4	
3-12	"	"	2,361	2,124	0.649	16.48	--	1.510	38.35	78.9	
3-13	"	"	1,951	1,755	0.618	15.69	--	1.295	32.89	67.6	
3-14	"	"	2,351	2,115	0.650	16.51	--	1.560	39.62	81.5	
3-15	"	"	2,396	2,156	0.652	16.56	--	1.600	40.64	83.6	
3-16	--	--	--	--	--	--	2.5	--	--	--	Did not forge
3-17	1,842	1,005	1,897	1,707	0.616	15.64	4.5	1.285	32.63	67.1	
3-18	1,983	1,083	1,912	1,720	0.614	15.59	5.0	1.445	36.70	75.5	
3-19	2,006	1,096	2,414	2,172	0.653	16.58	--	1.555	39.49	81.2	
3-20	2,000	1,093	2,350	2,115	0.651	16.53	--	1.390	35.30	72.6	
3-21	"	"	2,333	2,099	0.653	16.58	--	1.380	35.05	72.1	
3-22	"	"	2,333	2,099	0.660	16.76	--	--	--	--	
3-23	"	"	2,417	2,175	--	--	--	--	--	--	
3-24	"	"	1,944	1,749	0.610	15.49	--	1.257	31.92	65.6	

[1] Average Values

[2] Tooth fill is measured radially along the tip of the gear tooth. Value reflects the amount of the tooth tip contacting the die (See Figure B-3)

[3] Percent fill is calculated by dividing fill measurement by the designed tooth length of 1.915 inches (48.64 mm)

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