# Computer Aided Design (CAD) of Forging and Extrusion Dies for the Production of Gears by Forming

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Material losses and long production times are two areas of conventional spur and helical gear manufacturing in which improvements can be made. Metalforming processes have been considered for manufacturing spur and helical gears, but these are costly due to the development times necessary for each new part design. Through a project funded by the U.S. Army Tank – Automotive Command, Battelle's Columbus Division has developed a technique for designing spur and helical gear forging and extrusion dies using computer aided techniques.

### Gear Forming Methodology

Gear manufacturing processes are highly specialized due to the complex geometry and high accuracy requirements of the gear teeth. Precision forming methods for gears offer considerable advantages including the reduction of material and energy losses during finish machining. However, to establish precision forming as an economical production technique requires the capability to design and manufacture dies with precise and reproducible dimensions with long life and at an acceptable cost.

The traditional method of forging and extrusion die design and manufacture is based on experience and trial and error. A preliminary die is made and a few parts are formed. Measurements are taken of the finished part and the die is adjusted accordingly. A second series of trials is conducted, and so on, until the final die geometry is obtained. Such a development program is required for every new design which makes the precision forming process economically less attractive, especially when complex and precise geometries are involved, as with spur and helical gears. Therefore, methods need to be developed to apply advanced computer aided design and manufacturing (CAD / CAM) technologies (finite element, metal forming and heat transfer analyses) to gear forming die design and manufacture. This approach benefits from the capabilities of the computer in computation time and information storage and allows the die designer to try various changes in the die design and the forming conditions, without trying out each new change on the shop floor.

### CAD / CAM Applied to Forging and Extrusion

In recent years, CAD / CAM techniques have been applied

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to various forging processes. The experience gained in all of these applications implies a certain overall methodology for CAD/CAM of dies for precision and/or near-net shape forming. This computerized approach is also applicable to precision cold and hot forming of spur and helical gears, as seen in Fig. 1. The procedure uses as input: (a) the process variables and (b) the part (gear) geometry. The former consist of:

(1) data on billet material under forming conditions (billet and die temperatures, rate and amount of deformation),
(2) the friction coefficient to quantify the friction shear stress at the material and die interface, and
(c) forming conditions, such as temperatures, deformation rates, suggested number of forming operations.

Using the process variables and the part geometry, a preliminary design of the finish forming die can be made. Next, stresses necessary to finish form the part and temperatures in the material and the dies are calculated. 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. Knowledge of the forming stresses also allows the prediction of forming load and energy. The estimation of die geometry corrections is necessary for obtaining close tolerance formed parts and for machining the finish dies to exact dimensions. The corrected finish die geometry is used to estimate the necessary volume, and the volume distribution in the billet or the preform. Ideally, a simulation of the metal flow should be conducted for each die design. This is a computerized prediction of metal flow at each instant during forming. This simulation is mathematically quite complex and can only be performed at this time for relatively simple parts. In more complex applications, die design can be determined by computerized use of experience-based formulas.

### Two Phase Approach

The present study is still in progress and is being conducted in two phases as follows:

- Phase I
  Computer Aided Design (CAD) of forming dies.
- Phase II
  Computer Aided Manufacturing (CAM) of the forming dies and demonstration of the effectiveness of CAD/CAM by forming (forging and/or extrusion) a set of spur gears and a set of helical gears.

Fig. 1 – Descriptive Computer Aided Design Procedure for Finish Forging Dies

The Phase I work and the Phase II spur gear extrusion trials have been completed. A simplified flow diagram for the computer aided design and manufacturing of forging and extrusion dies for spur and helical gears is shown in Fig. 2. Using the overall outlines of Figs. 1 and 2, the die design effort was dividied into four tasks:

1. Definition of gear and gear tooth geometries.
2. Prediction of forming load, pressure and stresses.
3. Estimation of tool deflections, shrinkage and corrections.
4. Development of an interactive, graphics based computer program for performing Tasks 1 through 3.

### Generating the Gear Tooth Geometry

To define the tooth geometry, certain gear and/or cutting tool parameters must be specified. Some additional data pertaining to the mating gear may also be required in certain instances. All the data required for the computations can be obtained from a "summary sheet" developed by gear designers (Fig. 3) and also the geometry of the cutting tool (Fig. 4). With this data, standard gear equations are used to calculate the X and Y coordinates of the points describing the gear tooth profile.

The basic geometry of a spur gear tooth is seen in Fig. 5, with the following major definitions (1):

- addendum –
  the radial distance between the top land and the pitch circle
- backlash –
  the amount by which the width of a tooth space exceeds the thickness of the engaging tooth on the pitch circles
- circular pitch –
  the distance, measured on the pitch circle, from a point on one tooth to a corresponding point on an adjacent tooth
- clearance –
  the amount by which the dedendum of a gear exceeds the addendum of its mating gear
- dedendum –
  the radial distance from the bottom land to the pitch circle
- diametral pitch –
  number of teeth on the gear per inch of pitch diameter

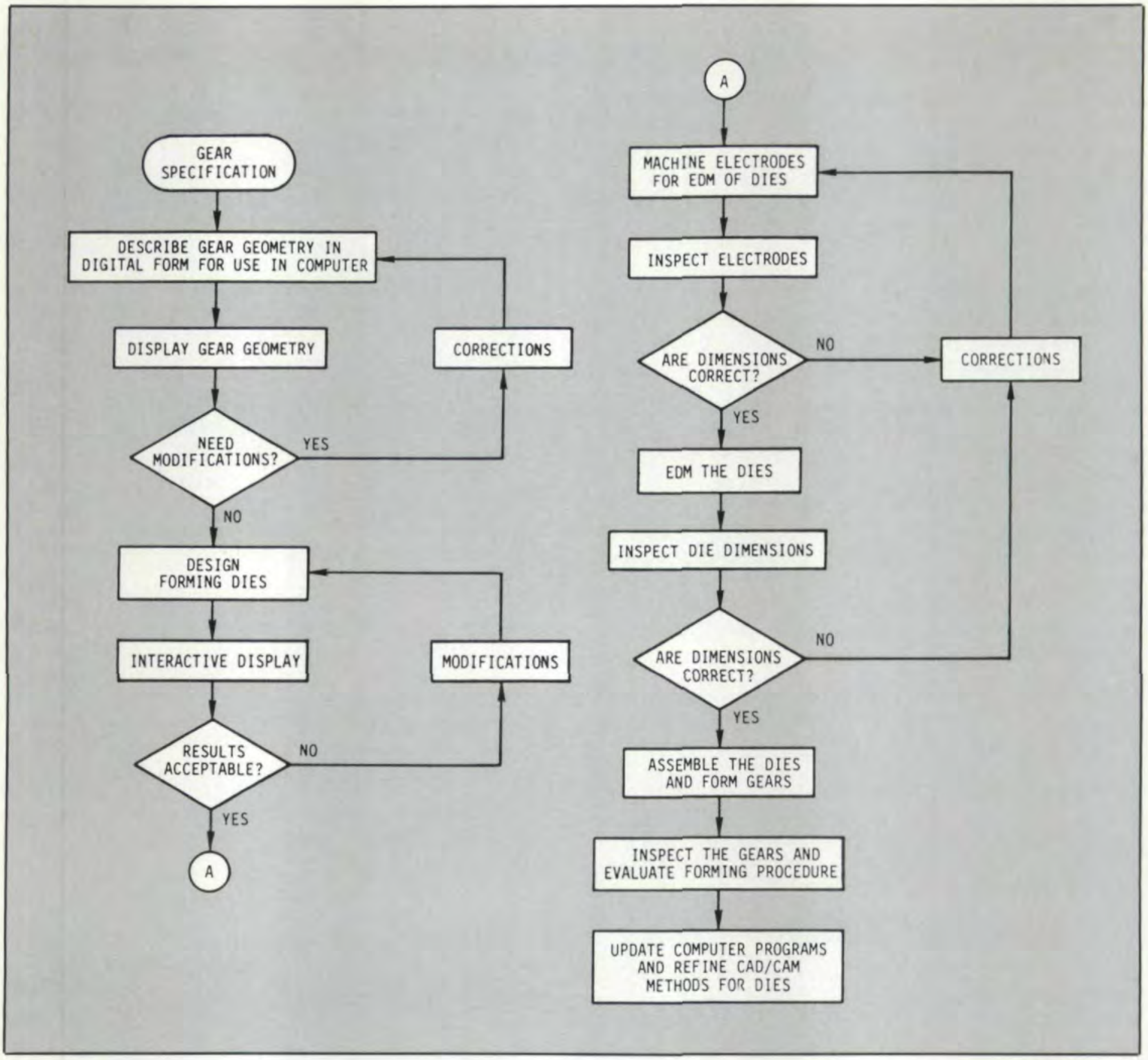


**Fig. 2** – General Procedure for the Design of Gear Forming Dies

- pitch diameter – diameter of the theoretical pitch circle which is tangent to the corresponding pitch circle on a mating gear

The majority of the gears produced by conventional cutting methods are either hobbed or cut using a shaper cutter (2). In this study, for defining the tooth geometry, standard equations were used to simulate the gear cutting process (3-7). These equations are included into a computer program, called GEARDI, as discussed later.

### Forming Load Prediction

To determine the elastic deflection of the forming dies, stresses acting on the die during the forming processes must be known. This stress analysis is necessary to obtain not only the elastic deflection, but also to calculate the forming pressure and load.

### Extrusion

The extrusion process is seen schematically in Fig. 6. The punch load required to extrude a spur or helical gear is determined by estimating the following forces:

- the ideal deformation force,
- the force due to internal shear at the die entrance and exit,
- the friction force along the die walls and the punch.

Using the slab method of analysis, the equations for the punch force were determined and programmed.

| DRAWING INFORMATION FOR: A DRIVEN COUNTER SHAFT | | ENGLISH (INCH) | METRIC (MM) |
|---|---|---|---|
| IDENTIFICATION NUMBER | | 81.0220 | 81.0220 |
| SET NUMBER | | 810.0123 | 810.0123 |
| NUMBER OF TEETH | | 32. | 32. |
| NORMAL DIAMETRAL PITCH (MODULE) | | 10.0000 | 2.540 |
| NORMAL PRESSURE ANGLE | | 19.0000 | 19.000 |
| HELIX ANGLE | | 31.5739 | 31.574 |
| HAND OF HELIX | | LEFT | |
| LEAD | | 19.2000 | 487.680 |
| TRANSVERSE DIAMETRAL PITCH (MODULE) | | 8.5197 | 2.981 |
| TRANSVERSE PRESSURE ANGLE | | 22.0064 | 22.006 |
| MAXIMUM OUTER DIAMETER | | 4.079 | 103.60 |
| MINIMUM OUTER DIAMETER | | 4.069 | 103.35 |
| MAXIMUM TIP CHAMFER DIAMETER | | 4.049 | 102.84 |
| MINIMUM TIP CHAMFER DIAMETER | | 4.039 | 102.59 |
| THEORETICAL PITCH DIAMETER | | 3.7560 | 95.402 |
| MINIMUM ROOT DIAMETER | | 3.511 | 89.18 |
| BALL/PIN DIAMETER FOR (MOP) | | 0.2160 | 5.486 |
| MAX. MEAS. OVER PINS (MOP) | | 4.1716 | 105.958 |
| MIN. MEAS. OVER PINS (MOP) | | 4.1681 | 105.870 |
| MIN. CALIPER MEAS. (4) TEETH | | 1.1056 | 28.082 |
| MAX. CALIPER MEAS. (4) TEETH | | 1.1071 | 28.121 |
| MEAN FACE WIDTH | | 0.875 | 22.23 |
| MIN. NORM TOPLAND (MAX. O.D. W/O CHAM) | | 0.029 | 0.74 |
| MIN. THEO. NORM. CIRC. TOOTH THICKNESS | | 0.1626 | 4.130 |
| TOOTH THICKNESS @ HALF OF WHOLE DEPTH | | 0.1764 | 4.481 |
| CASE DEPTH | | .023/.033 | 0.59/0.83 |
| MAX. PITCH DIAMETER RUNOUT (TIR) | | 0.0025 | 0.063 |

| | | ROLL ANG. | RADIUS | RADIUS |
|---|---|---|---|---|
| 051 DATA | @ MAX. OUTER RADIUS | 34.95 | 2.0395 | 51.803 |
| | @ MAX. END OF ACTIVE PROFILE | 33.99 | 2.0245 | 51.422 |
| | @ MAX. HIGH CONTACT POINT | 30.30 | 1.9697 | 50.030 |
| | @ OPER. PITCH POINT | 25.02 | 1.9000 | 48.260 |
| | @ MIN. LOW CONTACT POINT | 22.42 | 1.8697 | 47.491 |
| | @ MIN. START OF ACTIVE PROFILE | 17.45 | 1.8202 | 46.233 |
| | @ START OF INVOLUTE CHECK | 16.72 | 1.8138 | 46.070 |
| | @ BASE RADIUS | 0.00 | 1.7412 | 44.226 |
| 061 DATA | MAX. LEAD VARIATION | | 0.0004 | 0.010 |
| | MAX. LEAD RANGE | | 0.0008 | 0.020 |
| | CROWNING IN MIDDLE 80% OF TOOTH | | .00000/.00050 | .000/.012 |
| 071 DATA | MAX. RUNOUT (T.I.R.) | | 0.0025 | 0.063 |
| | MAX. TOOTH TO TOOTH COMPOSITE VAR. | | 0.0008 | 0.020 |
| | MAX. TOTAL COMPOSITE VARIATION | | 0.0032 | 0.081 |
| | MAX. PITCH VARIATION | | 0.0004 | 0.010 |
| | MAX. PITCH RANGE. | | 0.0029 | 0.073 |

Fig. 3 – Example of A Typical Gear Manufacturer Summary Sheet Defining Gear Geometry

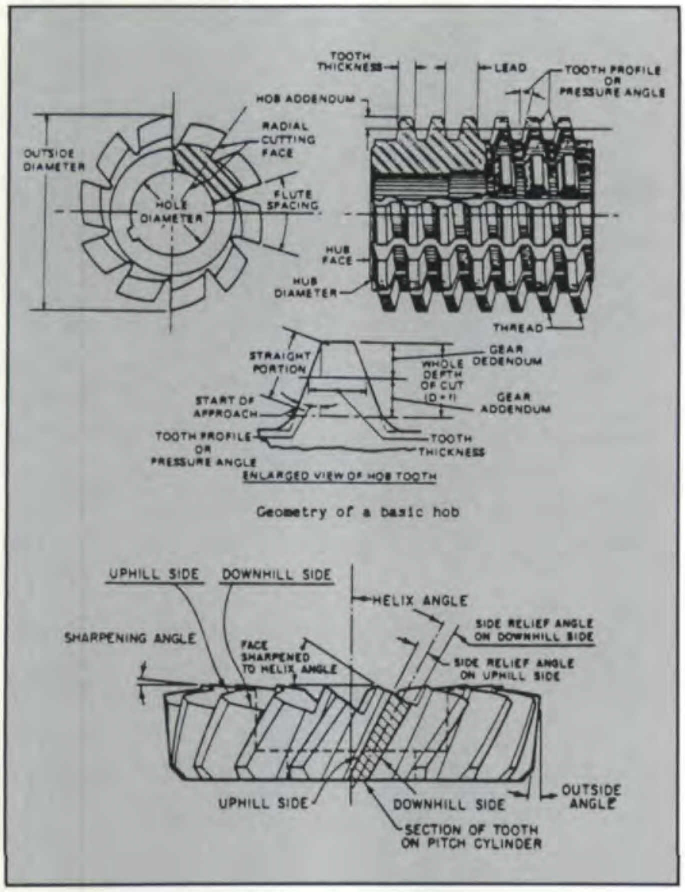


Fig. 4 – Geometry of A Hob and A Shaper Cutter

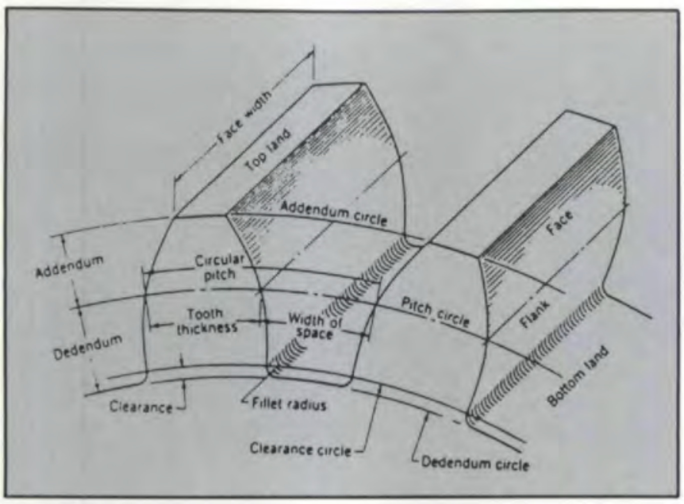


Fig. 5 – Gear Terminology

## Forging

A typical tool setup for forging of gears is shown schematically in Fig. 7. The punch force necessary to fill the tooth cavity by radial metal flow was also calculated using the slab method of analysis and empirical equations. Additionally, the forging load was estimated using a Finite Element Method (FEM) based program in order to verify the calculations made by the slab method and empirical equations. The results of the FEM analysis correlated closely with the empirical analysis.

## Estimation of Die Corrections

The geometry of the forming die is different from that of the formed gear because,

- The die insert is normally shrink fitted into the die holder causing a contraction of the die surfaces.
- In warm / hot forming, the dies may be heated prior to forming and further heated by the hot billet during forming. This causes the die insert to expand.
- During forming, due to forming stresses, the die surface deforms elastically.
- After forming, the gear shrinks during cooling from forming temperature to room temperature.

To obtain the desirable accuracy in the formed gears, each of the geometrical variations listed above was estimated and the die geometry corrected accordingly. Referring to Fig. 8, the original pitch radius is represented by R. Shrink fitting of the die causes the gear profile to shrink, hence the die must be increased by a corresponding amount, S. Similarly, increased die temperatures and forging pressures cause the die to expand. These two factors are compensated by the amounts H and E. Finally, a warm / hot formed gear will shrink during cooling; therefore, the die must be enlarged by the amount C. The results of the die correction analyses were used to alter the coordinates of the gear tooth profile to achieve the appropriate die geometry.

## Cutting the Die

A common method of die manufacture is called electrical discharge machining (EDM). The process uses an electrode, usually made of graphite or brass, which is the negative of

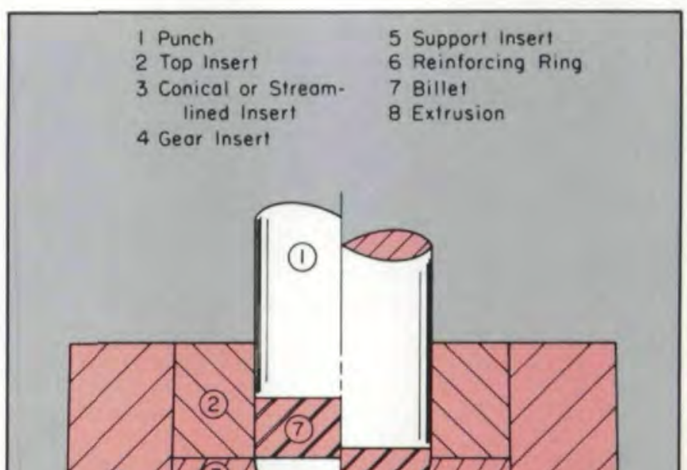


Fig. 6 – Schematic of the Extrusion Process

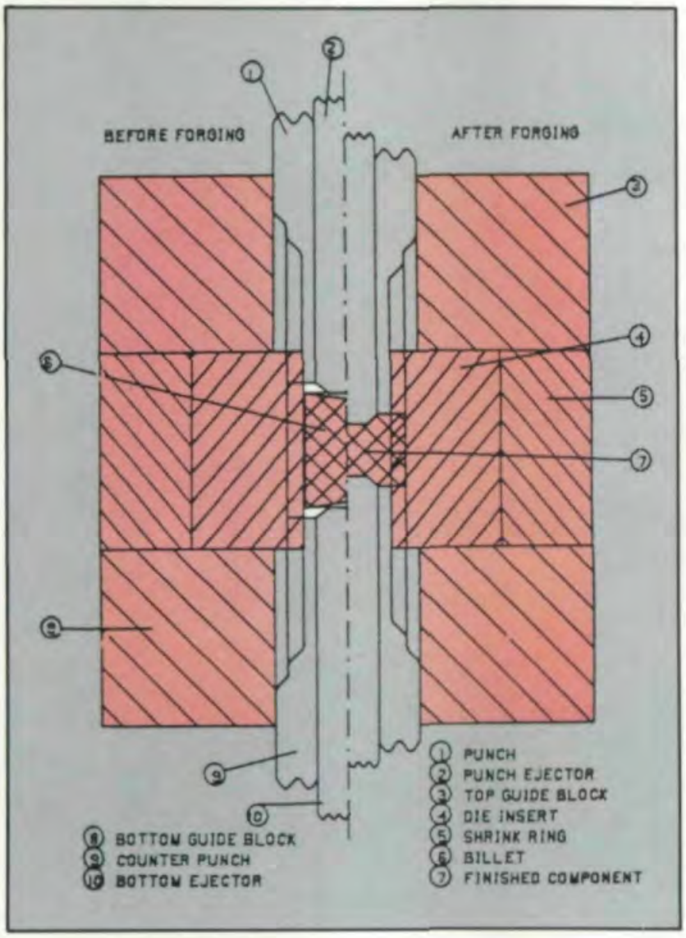


Fig. 7 – Typical Tool Setup for Forging Spur or Helical Gears

the die geometry. The electrode is brought close to, but not in contact with, the die material. An electrical current is allowed to arc across the gap which "burns" away the die material. Another form of this method of manufacture is called wire EDM. Current is passed through a straight wire that moves in two dimensions, burning the die geometry as it goes. Helical gear dies must be made by using a solid electrode but spur gear dies can be cut using either a solid electrode or a wire EDM process. In either case, a corrected set of gear tooth profile coordinates is needed. This new set of coordinates is computed by applying a correction factor to the radius vector from the center of the gear to each point on the gear tooth profile. The correction factor is a function of the values for S, H, E, and C as shown in Fig. 8.

As previously mentioned, the geometry of the die is different from the final gear geometry. When cutting the gear die using an electrode, it may be desirable to manufacture the electrode using a hob or shaper cutter specifically designed to cut the electrode geometry. The computer program, "GEARDI", allows the user to design this new cutting tool.

### Computer Program "GEARDI"

Using the equations developed in Phase I, a graphics oriented computer program called GEARDI was developed. The main functions of GEARDI are:

- define the exact tooth form of a spur or helical gear,
- compute the forming load required to produce the current gear design,
- compute the coordinates of the corrected gear geometry necessary for machining the EDM electrodes by taking into account the change in the die geometry due to temperature differentials, load stresses and shrink fitting, and,
- determine the specifications of a tool which can cut the altered tooth geometry on a conventional hobbing or shaper cutter machine.

This program enables the user to design spur and helical gears, predict tooling loads and pressures, estimate metal flow for forming the gear, and define the geometry required to manufacture the tooling using conventional or wire EDM. Several examples of gears, currently being forged in industry, were tested in the GEARDI computer program. The predicted forging loads were within 10 percent of the actual loads measured during production runs.

GEARDI is an interactive, graphics-oriented program which runs on Digital Equipment Corporation VAX 11/780, 11/750, and PDP-11/44 computers. It is a menu driven program that allows the user to select various options from a pre-defined list. Fig. 9 is a simplified flow diagram of the program depicting the various menu options available to the user. One convenient feature, the "COMPARISON DISPLAY" option, allows the user to superimpose two gear profile drawings on the computer and determine the maximum difference between the two profiles. Fig. 10 shows the superposition of an original spur gear tooth profile and the corrected geometry which was determined by the program for a specific set of forming conditions.

The GEARDI program has powerful application possibilities, not only in the area of metalforming, but also in the area of gear and gear train design, with its ability to

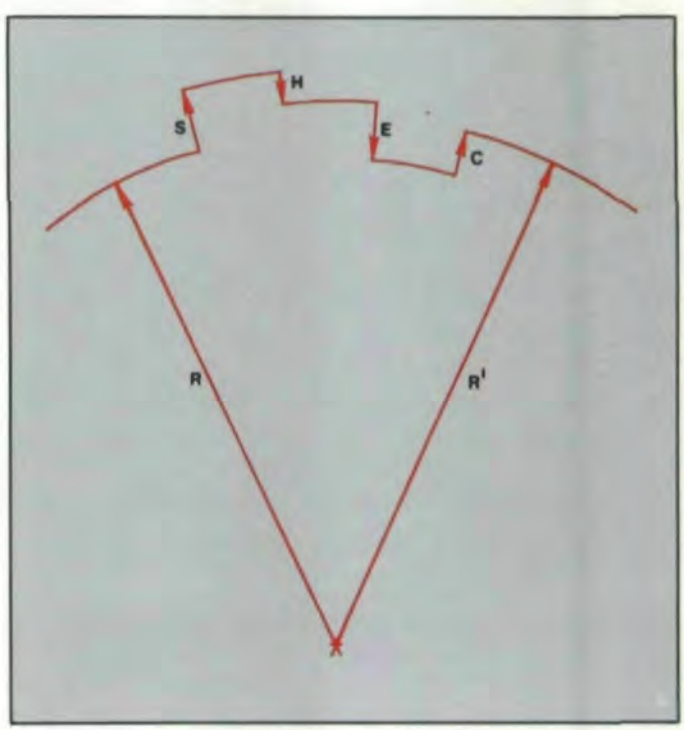


Fig. 8 – Correction to Gear Geometry (Symbols Explained In Text)

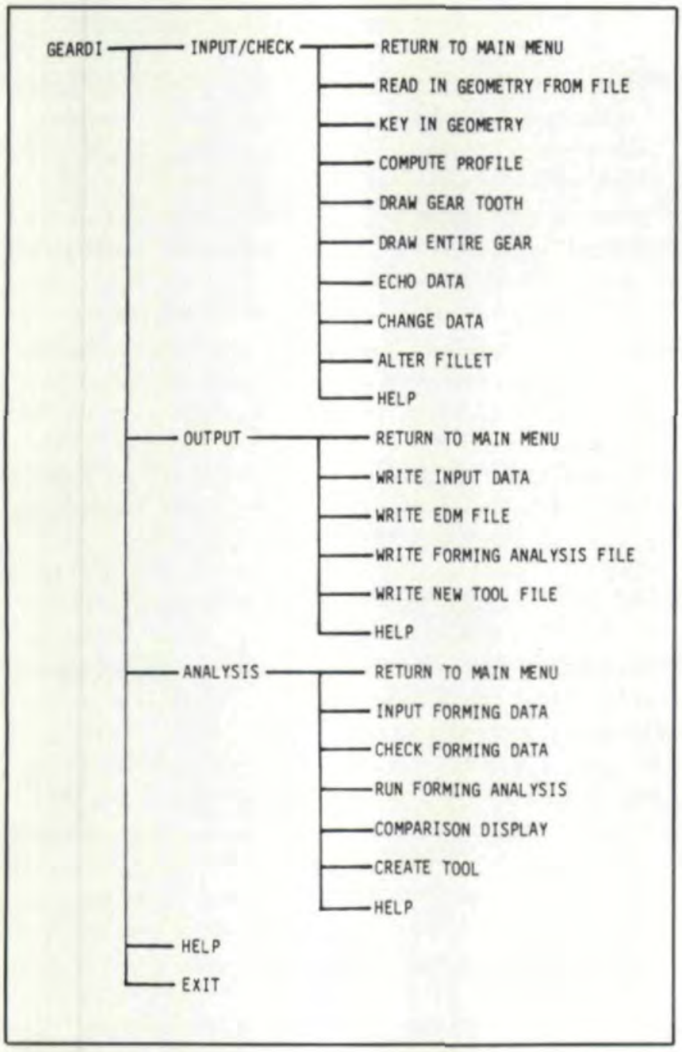


Fig. 9 – Flow Diagram for the Computer Program GEARDI

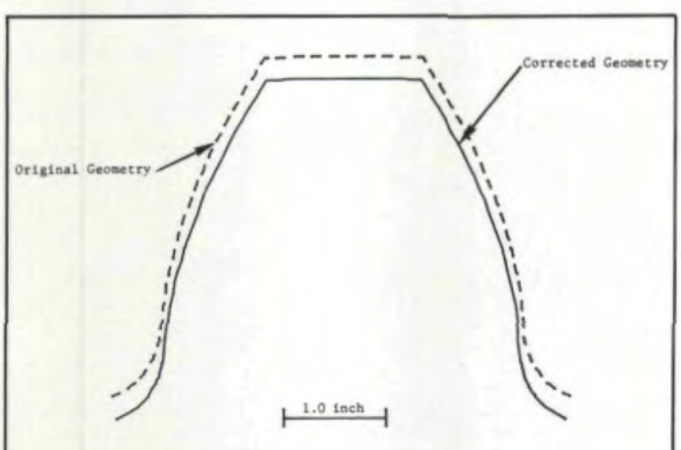


Fig. 10 – Computer Program Display of the Original Gear Tooth and the Corrected Gear Tooth Geometry

design hobs and shaper cutters and to modify the fillet from a trochoidal shape to a circular shape.

### Spur Gear Extrusion Trials

Fig. 11 shows a picture of the tool setup for the spur gear

Fig. 11 – Tool Setup for Spur Gear Extrusion Trials

extrusion trials, conducted at Battelle's Columbus Division using a 700-ton hydraulic press. The gears were extruded using a "push-through" concept. Each gear is first partially formed and left in the die while the punch is retracted. A second billet is placed on top of the partially formed gear and the press is cycled again. During this cycle, the partially

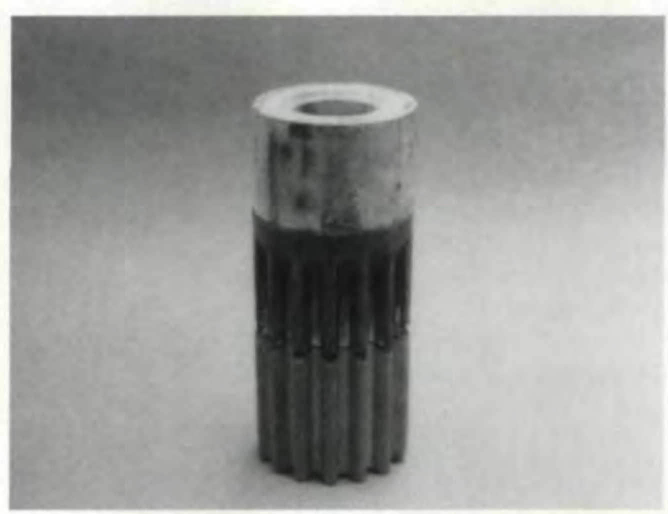

Fig. 12 – Sequence of Parts For Extruding Spur Gears. Billet is on Top, Partially Formed Gear is in the Middle, and Complete Extruded Gear is on the Bottom.

Fig. 13—Extruded and Shot-Blasted Spur Gear

formed gear is finish formed and pushed through the die, dropping out the bottom of the die. Fig. 12 shows the sequence of parts in the tooling. Once formed, the teeth on the gear are not machined further. A fixture which holds the gear on the pitch line of the teeth is used to finish machine the inside and ends of the gear. The spur gear formed in these trials was designed to be an AGMA quality class 8 gear. Measurements taken on the extruded gears indicated a gear of between AGMA quality 7 and 8. An extruded gear which has been shot-blasted is shown in Fig. 13.

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E-2 ON READER REPLY CARD



## ANALYZING GEAR TOOTH STRESS . . .


*(continued from page 15)*


Having established that stress levels vary in a predictable and quantitive way, work has begun on correlating the stress data obtained from the finite element stress program to sources of experimental data. Two parallel programs are now underway to provide such correlation. The first program will analyze several hundred fatigue test data points from full scale axle tests on a four square fatigue tester. The purpose of this program is to establish a reliable S-N curve for each of the modes of fatigue failure; e.g., bending fatigue and subsurface shear. The second program will involve fatigue data obtained from simulated gear tooth specimens using a closed loop hydraulic tester. The test data obtained from the simulated gear tooth specimens will be used to augment the data obtained from the full scale axle tests thus providing a relationship between S-N curves for various materials and heat treatments to the S-N curve obtained from full scale testing. The successful completion of this final step should result in establishing the finite element gear strength program as a powerful gear analyzing program for the design of bevel and hypoid gears.

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E-1 ON READER REPLY CARD