Simultaneous Consideration of Process Development and Die Design for Cold Forming a Fuel Injector Nozzle

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Higher strength and tighter dimensional tolerance is desired for the injector nozzles to attain high injection pressures for lower NOx and particulate emissions. Cold forming is an alternate method which can provide these characteristics replacing the present machining operation. Upset tests were carried out to study the flow stress properties for selecting a suitable material for this part. A knowledge-based system was used to design the die angles and a multi-stage cold forming sequence process to manufacture the injector nozzle. Finite Element Modeling was used to do the punch design and to optimize the punch loads and punch pressures for each stage of the forming process. Initial sequence design was modified based on the results of numerical modeling. The tooling was designed and experimentation was done to verify the formability and material flow.

1 Introduction

Recently there has been a growing emphasis on making automotive parts by net shape manufacturing. Primary issues to be considered are manufacturability, part cost, quality and achievement of desired mechanical and physical properties. The individual manufacturing process determines the part properties as well as the production costs. Thus, making the right choice of a process that is cost-effective for the required production volume and yet meets the design requirements, is extremely important.

Fuel injection systems are a very important part of the engine in determining the performance characteristics. With the rapid development in the technology of the electronic control in the injection systems for diesel engines, it is important to make injector components that can withstand high pressures for a longer service life. The on-highway applications are demanding an injector life in excess of 15,000 hours. Nozzles are the most critical part of the injector which need very precise design and manufacturing for meeting today's requirement.

Higher strength and tighter dimensional accuracy is desired for the injector nozzles in order to attain high injection pressures for lower particulate and NOx emissions. Reduction in the particulates and NOx not only gives a cleaner environment, but also helps improve the fuel efficiency of the engine thereby helping in the conservation of natural resources.

The fuel injector nozzles are currently made by machining. The starting material is steel bars which are fed to the machining centers. The outer profile of the nozzle is first turned on these machines. The inside cavity is then drilled, spray holes EDMed and finally the seat area is ground after the heat treatment process. These processes are expensive as very tight tolerances are required. Special tools and grinding operations are needed to make the part successfully.

Cold forming can be an alternate method for making the injector nozzle which can provide the desired characteristics replacing the present machining operation. Forming of the nozzle can also give a better control on the sac volume which plays a major role in determining the performance characteristics. However the difficulties may be encountered due to:

(a) the small dimensions of the part, and
(b) the precision required on the formed surfaces.

Conventional cold forging processes in the industry make use of upsetting followed by piercing for pressure relieving as shown by Kudo (1990). He has reported the use of intermediate annealing and lubrication. A combination of hot or warm forging and subsequent cold forging or coining operation has been used to produce bevel gears and constant velocity joint components using radial extrusion and closed die forgoing. Kondo (1984) has suggested the use of relaxing a constraint on the tool in forming spur gears. The unconstrained inaccurate portion of the product is finished in a subsequent operation.

Current design practices make use of multiple-action processes. In this process more than two active components of the tool set-up move in the same and/or different direction simultaneously or sequentially to deform or support a workpiece at one station. A multiple-action press or a single-action press installed with hydraulic or mechanical actuator is used.

The fuel injector is a very slender part. The punches required would be long and thin. Punch deflections, punch life and punch breakage would be some of the key issues. The dies would have deep cavities with large surface area to volume ratio which makes it difficult to eject the part. Extrusion angles and corners in the part are not typical for cold forging. These might result in non homogeneous material flow. Die life has to be taken into account as tooling is very expensive.

Thus, there is a need for simultaneous consideration of process and die design. Both these steps need to go hand in hand following the Concurrent Product and Process Development philosophy. This helps to eliminate costly expenditure in experimenting with different manufacturing techniques and speeds up the product implementation by months and years. The latest CAE tools can be effectively utilized to achieve these goals.

2 Research Issues and Approach

An analytical study was undertaken to look into the forming of a high pressure fuel injector nozzle. Cold forming of the nozzle as compared to the present machining operation was

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thought of as an alternative process because of the following reasons:

(i) elimination of costly machining operations,
(ii) better strength in the sac region due to work hardening, and
(iii) good concentricity between the inner and outer surfaces of the injector nozzle.

It is desirable to make the injector nozzle from stainless steels. They are preferred because of their strength and corrosion resistance to diesel fuels. A number of problems have to be addressed in making this part by multistage cold forming with these materials.

(1) Very little data on the flow stress and strain properties of these materials is available in literature. Thus, upsets tests have to be carried out to obtain the flow stress properties for these materials and to determine the workability limits.
(2) Stainless steels cannot be adequately acid pickled. Consequently conventional lubricating techniques (pickling and phosphate treatment) are not effective and galling results due to lubricant breakdown. Lubricants like copper plating (which may be etched away later), molybdenum disulfide or oxalates can be used.
(3) The size of the part is too small for conventional cold forming. It poses problems like handling, distortion, precision and ejection of the part.
(4) No prior experience of cold forming this part exists in the US.

The research approach adopted was to use Computer Aided Engineering techniques for process planning, conceptual design and detail design optimization. This enabled saving of time and capital expenditure. Experimental tests to study the material characteristics and two dimensional finite element simulation combined with knowledge-based system analysis were used to design a multi-stage sequential process to manufacture the injector nozzle. An interface program provides an efficient data exchange after process simulation for punch stress analysis.

The problem was pursued by first trying to identify suitable materials which can be used to make the part. Identification of the material involves a number of issues like formability and workability. The flow properties of the steels which were being looked into were not readily available in literature. These steels have not been used in the past for the application they are intended for. Material tests can provide the necessary information - whether the material is workable or will it crack after a certain amount of deformation. Upset tests have been used in the past to determine the flow stress properties. Rastagaev (1940), Kudo et al. (1968), Douglas and Altan (1975), Meester and Tozawa (1979), Osakada et al. (1981) and Yaguchi and Rusia (1990) have reported the use of these tests in the past.

To form the part by cold forming, a sequence of operations may be required. The desired part has internal cavity and profiles which cannot be formed in one step. The sequences available in literature have been derived by experience and experimental forming. Therefore, a knowledge based system can be used to design these sequences. The design of operational sequences for multi-stage cold forming operations is one of the critical responsibilities of the process planner. The mechanical properties of the finished product as well as the tooling and operating costs are greatly affected by preforming steps.

Recently, a number of CAD procedures for cold forging process design have been developed. They consist of modules to assist the user in generating complete forging sequences for classes of components according to design rules. These modules are incorporated in the programs and formulated on the basis of precedence and grouping relationships and process limitations relevant to each operation. Iterations are necessary to achieve technical feasibility as well as good economic balance starting with the initial design.

Bariani et al. (1987) have reported the development of an interactive program aimed at assisting the user in analyzing for suitability of the forming sequences for multi-stage in cold forging of rotationally symmetric parts. This program gives the load-peak requirements and the strain distributions in the part. Bariani and Knight (1988) have discussed the development of a knowledge based system to develop sequences for multi-stage cold forging of solid and hollow axisymmetric parts. Their approach is based upon a backward direction of the generative process and takes advantage of the design rules which govern:

(a) the recognition of operations,
(b) determination of the relevant deformation, and
(c) sequencing and grouping of the different operations.

Badawy et al. (1985) have reported the development of a computer-aided system called "FORMNG" for designing the forming sequence for multi-stage forging of round parts. Given the billet diameter, the final part geometry and the material and friction conditions, this program recognizes the final part geometry, applies established design rules on different forming operations, determines and displays the forming sequence, and calculates the forming loads to perform each forming operation. The predicted forming sequence is determined automatically using pattern recognition.

Lange and Du (1988) have described a formal approach to the forming sequence design of axisymmetric parts using AI-state space model. The design follows the simplification principle of the forming sequence design. Noack (1973) has suggested a computer-aided determination of operation sequence and costs in cold forging.

A knowledge-based computer aided cold forming sequence design system called "FORMEX" (Kim et al., 1992) has been developed at the ERC for Net Shape Manufacturing at Columbus, Ohio. This program derives the design rules from sequences which have been successfully tried and established in the industry. FORMEX has two major components:

(i) a Design System (DS) for forming sequence design, and
(ii) an Evaluation System (ES) for verifying the forming sequences developed by the Design System.

This system was used in the present study to do the cold forming sequence design. FORMEX can also be used to design the die angles for optimum material flow.

The fuel injector nozzle is an axisymmetric part. A schematic of a typical part is shown in Fig. 1. Process modeling of the forming operation using Finite Element Modeling (FEM) can help us accurately predict the loads and tooling pressures generated. The forming of the injector may be done using a number of sequences. To evaluate all the sequences using FEM is very expensive, time consuming and tedious. A lot of computational time is required too. Thus, it is necessary to design the best sequence using FORMEX and use FEM for refining and fine tuning the design. FEM can help in the punch design by estimating the pressures and loads experienced. The punch will most probably be long and slender in the last step. Thus it is necessary to design a punch with adequate service life and low deflections.

DEFORM is a special purpose finite-element code which can be used to simulate large deformation problems such as metal forming operations. It has been successfully used in the past to solve industrial problems as demonstrated by Oh et al. (1992). It is based on a rigid-viscoplastic formulation and can be used for various class of materials such as viscoplastic, thermoplastic and powder materials. It can handle plain strain as well as axisymmetric geometries and the analysis can be performed for isothermal or non-isothermal conditions. In these investigations DEFORM was used for sequence design and evaluation.

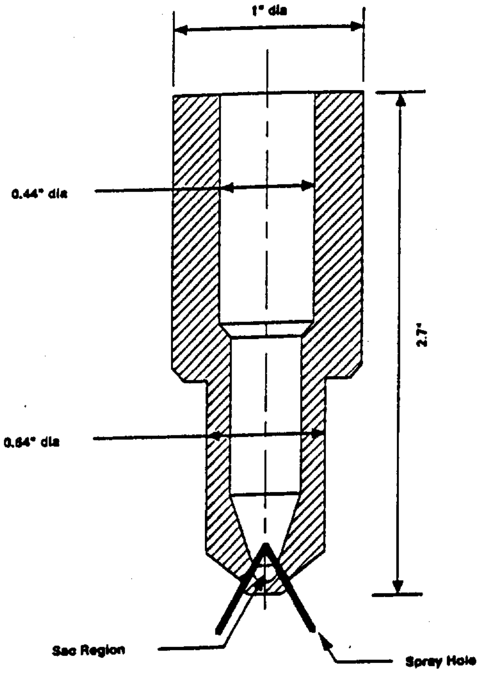


Fig. 1 A sectional view of a fuel injector nozzle

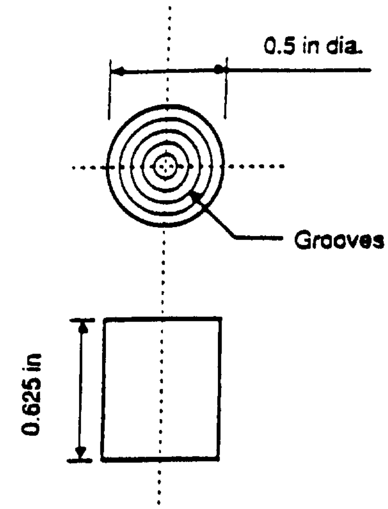


Fig. 2 A schematic of the test specimen

3 Upset Tests to Determine the Stress-Strain Data

The materials used for making the injector nozzles are mostly alloy steels. Most commonly used steels are chromium steels, molybdenum steels and nickel-chromium steels. A high carbon content with high chromium is characterized by high hardness and wear resistance. In the nickel-chromium alloys, the effect of nickel is to impart toughness and ductility. Molybdenum steels have good high-temperature hardness and strength.

Six steels were identified as possible materials for making the injector nozzle—501, 440A, 440C, 431, 17-4PH and 13-8Mo. To find the flow stress data for these steels, uniform compression tests with smooth dies and specimens having concentric grooves on the top and bottom faces were carried out. The following sections describe the test specimens, the die platens used for upsetting, testing procedure, lubricants and the results of these experiments.

Test Specimens. The test specimens used for this study were machined from bars which had been previously heat treated. Although most of the materials were received in an annealed condition, it was decided to do a further anneal to eliminate any residual longitudinal strains that may have resulted from the cold drawing of the incoming bars.

The specimens were machined to a final diameter of 0.5 inch and a height of 0.625 inch. Concentric grooves with 0.05 inch pitch and about 0.01 inch depth were machined on the end faces of the specimens. A schematic representation of the specimens is shown in Fig. 2. The concentric grooves help trap the lubricant between the die platens and the specimen while the workpiece undergoes a continuous deformation.

Die Platens. The die platens were machined out of AISI 4340 steel and through hardened to a hardness of Rc 52. The platens were made 3 inch thick and ground on the faces that would come in contact with the specimen. A threaded hole was machined in the center of the top platen so that it can be held in a fixture on the testing machine. A schematic of the platens is shown in Fig. 3.

Testing And Results. A Tinius Olsen testing machine was used to do the upsetting. A strip chart recorder fitted to the testing machine allowed continuous monitoring of the load and specimen deformation when coupled to a deflectometer unit mounted on the upper die platen. A pre-calibrated graph paper was mounted on the recorder to plot the load-stroke curve.

Teflon sheets with dry soap were used to lubricate the specimen at the top and bottom surfaces. It was then placed on top of the bottom platen. The top platen was moved down to upset the specimen. The specimens were deformed to 50 percent height each time. The entire deformation was done in five steps with relubrication at each step. Due to this reason, there was no significant bulge. Therefore the bulge correction factor was not applied. Each experiment was repeated twice and average value used to calculate the material constants. The true stress and true strain values were calculated from this data and plotted for each experiment. The power curve $\bar{\sigma} = K\bar{\epsilon}^n$ was used to fit the data to find the values of the strength coefficient K and strain hardening exponent n. The results are shown in Table 1.

It can be seen from the results that 501 steel is best suited for cold forming applications. It has the lowest value for the strength coefficient. The flow curve shows the true stress leveling off at 130 ksi. Its high strain hardening exponent helps in reducing the inhomogenity in extrusion operations.

It is seen from Table 1 that 13-8 Mo, 17-4 PH and 431 have high values of strength coefficients and low values of strain hardening exponents. The formability of 440C is very poor, as it cracked at a true strain of 1 in all the three experiments.

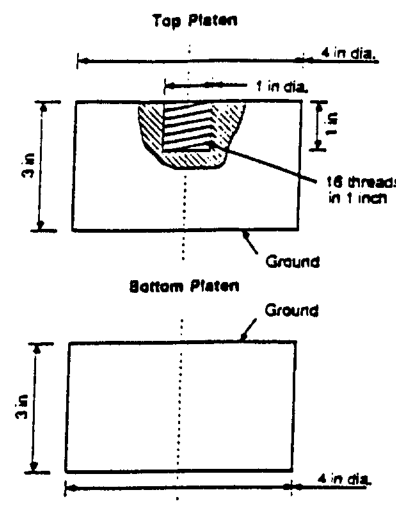


Fig. 3 A schematic of the die platens

Table 1 Values of material constants K and n for different materials

Material	K (ksi)	n
501	121	0.176
440A	142	0.157
440C	175	0.11
431	156	0.05
17-4 PH	190	0.065
13-8 Mo	184	0.025

However 440A can be a good second choice for cold forming operations.

4 Punch Pressure Analysis

Since the material selected after the above tests (501 steel) has high strength coefficient K, and large strains are expected during forming with punches of small cross-sectional area, it is necessary to do a punch pressure analysis. The punch is required to withstand very high pressures. Punch pressures of up to 350 ksi have been reported for tool steel punches in ICFG Data Sheets (1982). DEFORM was used for punch design because the effect of indentation on punch pressures cannot be studied using FORMEX. In addition numerical modeling can give pressures along the profile of the punch. This gives a better understanding of the material flow during the backward extrusion process.

During the deformation analysis using DEFORM, the dies are assumed to be rigid objects (which helps to reduce the computational time drastically). But the pressure distribution cannot be studied for the punch using DEFORM which neglects elastic analysis. The contact stress distribution is calculated as pressure on the contacting billet nodes. Thus it is necessary to transfer these pressures on the surface of the punch to get an idea of the punch pressures. After a punch mesh is created, the contacting border nodes of the billet may not coincide. Therefore, not only a data transfer, but also a data interpolation is necessary from the billet nodes to the punch nodes to obtain the correct pressure values on the punch node locations.

To carry out such an investigation in an effective manner, a program called TRANSFER was developed by Knoerr and Altan (1991). This program helped to automate the data exchange task. The program has the following features:

- All necessary data is extracted from the DEFORM database file;
- Edge pressures and forces on the contacting die elements/nodes resulting from the contact stresses are calculated;
- Pressure, forces and temperature data are written into separate Universal Files for upper and lower dies, and the billet;
- An indication of the accuracy of the data transformation is given by summing the force components in the x and y directions on the upper and lower die and comparing with the load estimates from DEFORM.

5 Sequence Design for Injector Nozzle Using Formex

The cold forming sequence design for the manufacture of the injector has been carried out using FORMEX. It helps us to get a quick idea of the average loads, pressures and strains that are generated during the forming process. The sequence design is an iterative procedure as can be seen from Fig. 4. Since the existing Sequence Library in FORMEX does not have a sequence for a part similar to the injector, a totally new sequence had to be designed. Thus a number of iterations were required to arrive at the final sequence.

The sequence design was started by designing the final geometry in DS. Since the part is axisymmetric, only one-half of the part is used to carry out the analysis. The part can be dimensioned conveniently in Design View. The volume of the material required can be calculated using a simple equation.

The preforms for different stages can be designed based on the operations required. The stages required for the manufacture of the injector nozzle were decided based on the sequences for similar parts found in the literature. While designing the preforms, volume constancy was taken into account from one stage to the other as the same workpiece moves ahead for further forming.

The sequence decided for the injector nozzle was:

Stage 1 - Forward extrusion combined with closed die upsetting.
Stage 2 - Backward extrusion.
Stage 3 - Forward closed extrusion.
Stage 4 - Backward extrusion.

It is desirable to get a uniform strain distribution in the part starting with the first stage. A uniform strain distribution results in good strength and hardness and provides a smoother grain flow. To get same strains in the top and bottom areas, we have to upset the top and forward extrude the bottom as suggested by Schey (1987). The starting billet diameter needs to be calculated to achieve the uniform strain distribution. With reference to Fig. 1, let

d_0 = starting billet diameter
d_1 = diameter of the forward extruded portion = 0.64 inch
d_2 = diameter of the upset portion = 1 inch

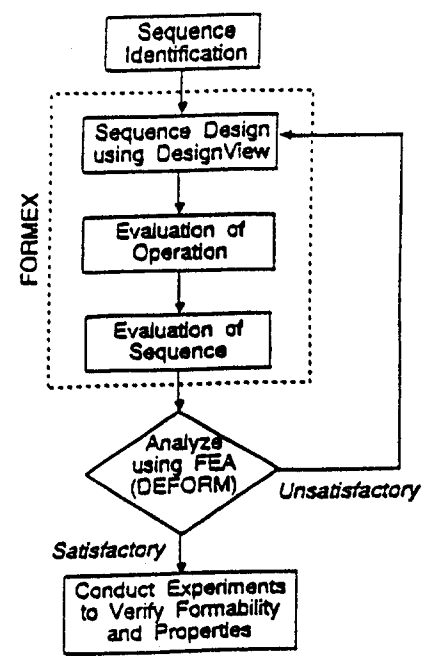


Fig. 4 Flow chart of cold forming sequence design using FORMEX and FEM

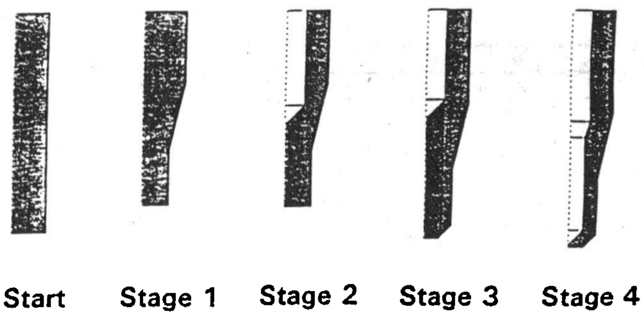


Fig. 5 Preform at the end of each stage

Strain in the bottom area due to forward extrusion

$$= \ln\left(\frac{A_0}{A_1}\right) \quad (1)$$

Strain in the top area due to upsetting

$$= \ln\left(\frac{A_2}{A_0}\right) \quad (2)$$

For uniform strain,

$$\ln\left(\frac{A_0}{A_1}\right) = \ln\left(\frac{A_2}{A_0}\right) \quad (3)$$

$$A_0^2 = A_1 * A_2 \quad (4)$$

For our example,

$$(d_0^2)^2 = (d_1^2)*(d_2^2)$$

$$(d_0^2)^2 = (0.64^2)*(1^2)$$

$$d_0 = 0.8 \text{ inch} \quad (5)$$

The next step is to evaluate each stage of the sequence designed above using the ES. The initial and final geometric parameters, the friction factor and the pre-strain are input into the ES. It then calculates the load, punch pressure etc. required for that stage.

The preform design for each stage of the sequence is shown in Fig. 5.

The punch pressures, loads and average strains for each stage of the initial sequence given by FORMEX are given in Table 2.

6 Design of Die Angles Using FORMEX

A number of design considerations have to be taken into account while designing the punch and dies for forming the part shown in Fig. 6. The angles have to be designed such that desirable material flow is obtained and the pressures kept to a minimum without sacrificing the strength.

FORMEX helps to get the optimum die angle for the forward and backward extrusion processes. The geometry shown in Fig. 6 was chosen for calculating the effect of die angles because it represents the configuration of the part at the end of last operation. The material flow will be most difficult and complex for the last stage due to large residual strains, stresses deep in the plastic regime and high hardness of the material. In addition, the punch will be long and slender in this stage. It is necessary to minimize the deflection of the punch in order to achieve good dimensional accuracy. Therefore it becomes necessary to design the dies such that material flow is smooth and minimum forming loads are required. A parametric study was carried out to find the effect of changing the die angles α and β on the loads required. The effect of changing the semi-cone angle of the die on the load is plotted in Fig. 7.

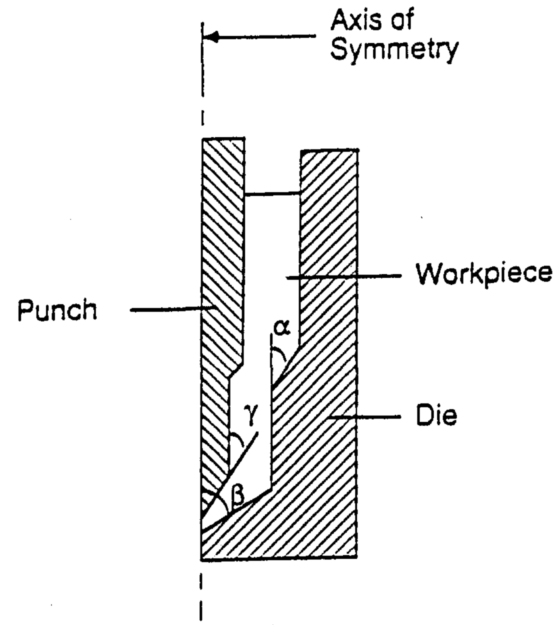


Fig. 6 Geometric factors considered for punch and die design

Angles α and β in the plots refer to the angles given in Fig. 6. Due to the strength requirements for the sac region of the fuel injector, angle β was chosen to be 45 deg. The load does not increase appreciably when this angle is selected. It increases by 4 tons (about 10%) if β is changed from 21.1 to 45 deg.

7 Punch Design Using Deform

To find the optimum punch angle γ for backward extrusion during the forming of the nozzle, the piercing process was simulated in DEFORM. Three semi-angles were selected to be studied for punch design: 35 deg, 45 deg and 55 deg. An interval of 10 deg on either side of 45 deg was chosen so that we get a measurable difference in the punch pressure. The punch pressures were studied for the three cases for an indentation of 0.5 inch of the punch into the billet. A 1 inch diameter billet and a punch with 0.44 inch diameter were used in the simulation.

The deformed meshes for the three punch angles are shown in Fig. 8. The punch pressures for each punch design are plotted in Fig. 9. It can be seen from Fig. 9 that the peak punch pressure is minimum for the punch design of 45 deg. In addition, the pressure distribution across the tip of the punch is more uniform for this design as compared to the other two. Hence a punch with semi-cone angle of 45 deg. was used to simulate the forming of the fuel injector.

Table 2 Forming data from FORMEX for the sequence in Fig. 5

	Punch Pressure (ksi)	Loads (ton)	Strain Increment
Stage 1	153.91	42.54	0.47
Stage 2	235.74	17.92	0.22
Stage 3	252.71	40.65	1.27
Stage 4	258.81	10.41	0.75

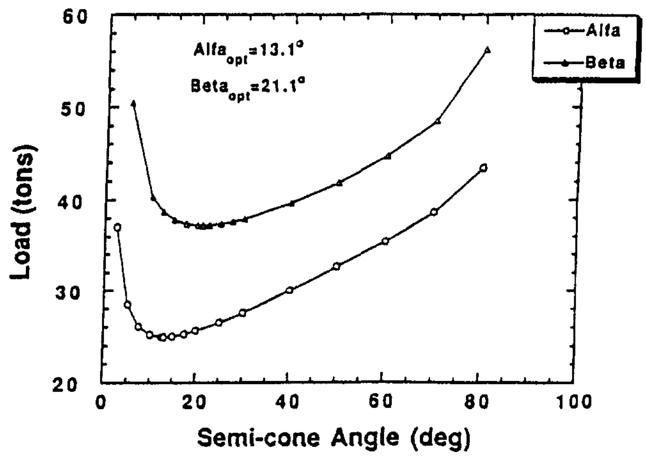


Fig. 7 Variation of semi-cone angle of the die using FORMEX

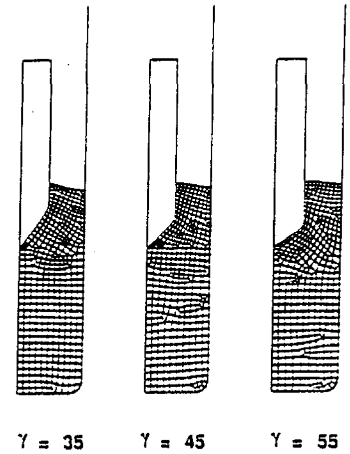


Fig. 8 Deformed mesh for each punch design (ref. Fig. 6)

8 Numerical Modeling for the Manufacture of a Fuel Injector Nozzle

Since the intent was to simulate the cold forming operation, isothermal analysis at room temperature was carried out. A constant shear friction factor of 0.08 at the die-workpiece interface was used as suggested for cold forming by Lange (1985). Since this is a large deformation process, automatic remeshing was used to prevent excessive distortion of the elements. The remeshing criterion for the mesh consisted of assigning weights to the controlling parameters: 0.2 to boundary curvature, 0.5 to strain-rate and 0.3 to strain. A higher weight was assigned to the strain rate and strain because the forming will give large plastic deformations.

Direct method of solution was used in the solver. Typically hydraulic presses are used for cold extrusion processes in the industry. These presses have a ram velocity of the order of 2 inch/sec. Therefore, the punch velocity was prescribed at 2 inch/sec. The workpiece was assumed to be plastic and the dies to be rigid.

To model the cold forming process, finite element simulations were carried out for a single strain rate. By theory, flow stress is a function of strain, strain rate and temperature. But the dependency on strain rate is stronger at elevated temperatures compared to room temperatures. Therefore it was decided to restrict the simulations to one strain rate only.

The Fuel Injector Nozzle is an axisymmetric part. Therefore half of the nozzle geometry was simulated in 2D using the axisymmetric mode of analysis in DEFORM. The geometric angles selected earlier were used for simulations. Material properties of 501 steel were used. The starting billet geometry was taken from the results of the sequence design using FORMEX. The simulation for each stage was considered to be complete when the dimensions of the preform reached those of the sequence design.

The punch and the die-insert geometry was changed at the start of each stage. The boundary conditions were initialized at the start of a new stage. To come as close as possible to the actual case, each stage was modeled progressively after the completion of the previous stage. This helped to take into account the strain and damage history carried over from the previous step.

At the end of simulation for each stage, TRANSFER was used to extract the contact stress distribution on the punch face. The step showing the highest load on the punch was used to study the punch pressure. Before this program could be used, an FE mesh had to be included in the DEFORM database for the punch. After the inclusion of the punch mesh, TRANSFER interpolated the contact stresses from the billet nodes to the punch nodes and element faces. The universal files were used to transfer the load and pressure data to the general purpose code I-DEAS.

9 Simulation Results

First the results for the initial sequence and then for the modified sequence are presented here. The deformed mesh for each stage of the initial sequence is shown in Fig. 10. The first step was to forward extrude the billet and then upset it. The second stage involves backward extrusion to form the top part of the nozzle. The third stage starts to give the outer shape of the sac region. The fourth stage forms the internal bore of the nozzle and forms the cup for the plunger.

The punch pressure distribution across the length of the punch is shown in Fig. 11. During the course of the simulations, it was seen that very high punch pressures (up to 400 ksi) are experienced in stage 4. The load-stroke curve for this sequence is shown in Fig. 12. A 125 ton press would be required for this stage. Thus it was necessary to modify this sequence.

The initial sequence was modified with an aim to reduce the overall punch pressures and the load in the third stage. Due to the small dimensions of the nozzle, the punch is slender and long. High punch pressures will lead to catastrophic failure. It was necessary to keep punch pressures close to 300 ksi for an M4 steel punch. To reduce the punch loads and pressures, FORMEX suggested to eliminate enclosed volume forming and minimizing large material displacements wherever possible. A closer look at the initial sequence shows that the shoulder on the punch in the third stage extrudes the whole part through the

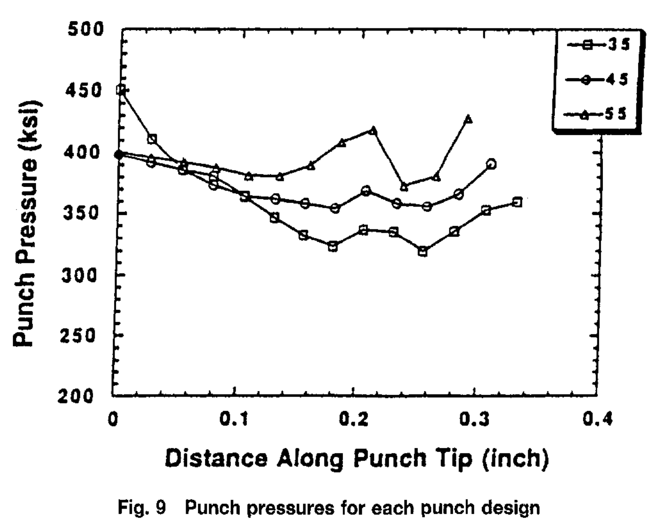


Fig. 9 Punch pressures for each punch design

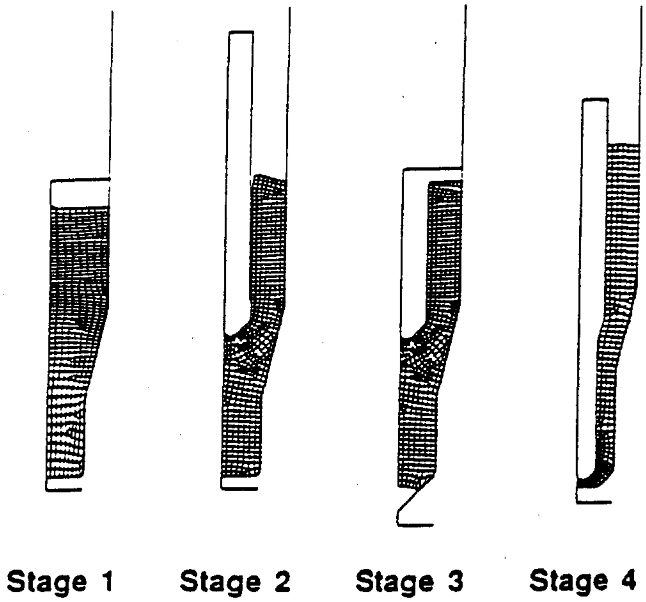


Fig. 10 Deformed mesh for each stage of forming for the initial sequence

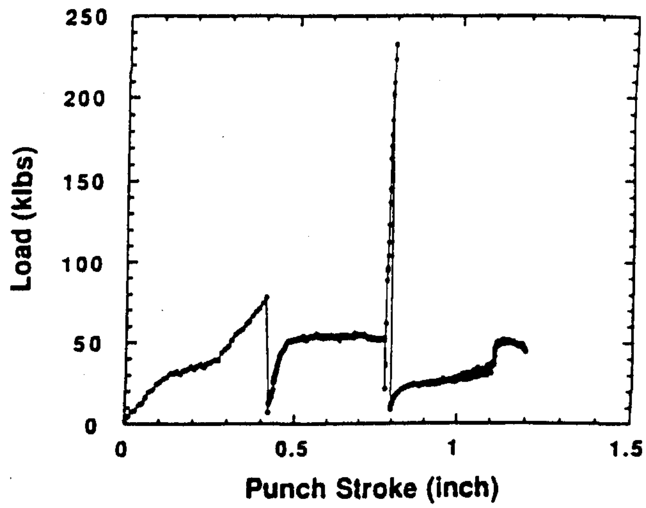


Fig. 12 Load-stroke curve for the initial sequence

die. Thus frictional forces are very high because of the large contact area. This shoulder was removed, which would help to reduce the punch pressure. The "sac" region would be formed with a punch moving upwards from the bottom using a multi-action press. This would help to reduce the loads and provide a tighter control on the wall thickness of the sac, which is critical. A punch moving upwards could aid in the ejection of the part at the end of the process. The modification of the initial sequence also helped in reducing one stage in forming of the nozzle.

The first stage of the modified sequence consisted of forward extruding and upsetting. The second stage consists of backward extrusion to form the inner diameter of the nozzle. Both the stages were designed with open bottom. This helps to reduce the pressures on the punch tip. The third stage consisted of forming the bottom of the nozzle and the sac region with the help of a punch moving upwards.

The deformed mesh for each stage of the modified sequence is shown in Fig. 13. The punch pressure distribution across the length of the punch is shown in Fig. 14. The maximum punch pressure attained in this case is about 300 ksi. The load-stroke curve for the modified sequence is shown in Fig. 15. It can be seen that the loads have drastically reduced as compared to the initial sequence. This sequence was selected for tooling design and experimentation.

10 Tooling Design

The design of dies and die assemblies for cold extrusion requires consideration of the following three points (ICFG, 1972):

(a) Operating Extrusion Pressure. The extrusion pressure mainly depends on:

(i) The flow stress of the workpiece material;
(ii) the type of process;

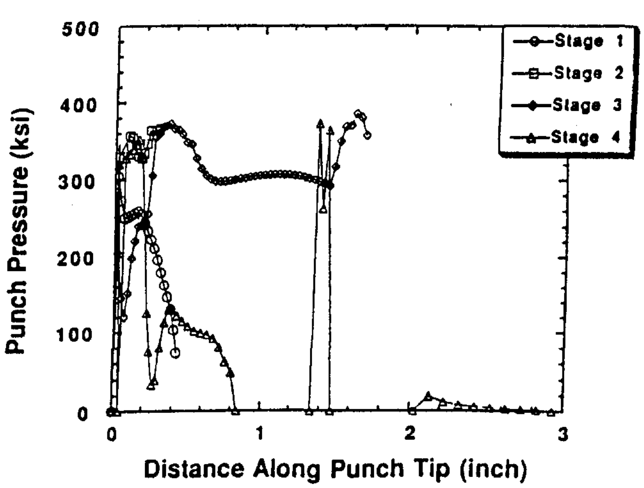


Fig. 11 Punch pressure distribution across the face of the punch for the initial sequence

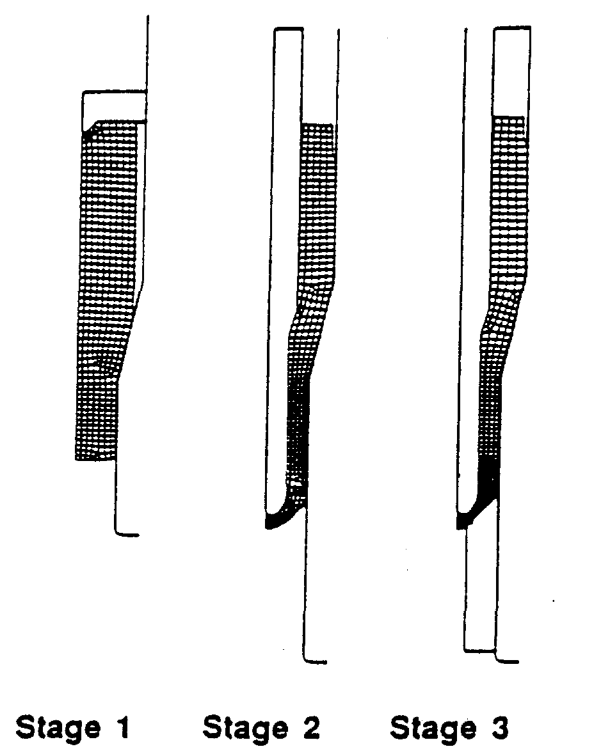


Fig. 13 Deformed mesh for each stage of forming for the modified sequence

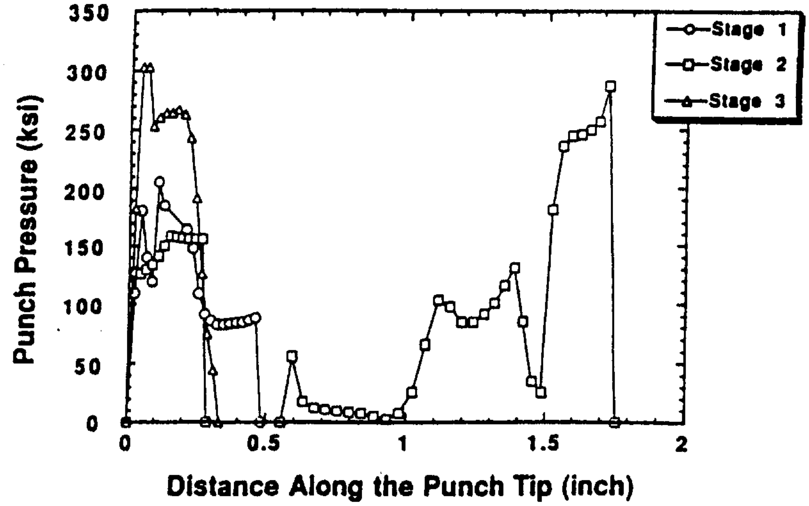


Fig. 14 Punch pressure distribution across the face of the punch for the modified sequence

(iii) the geometry of the die and slug or preform;
(iv) friction and lubrication.

(b) Overall Configuration of the Assembly and Geometry of the Die. Extrusion dies are generally very highly stressed. Dies are reinforced by one or more rings whose outer dimensions depend on the space available within the tool-set or press, and on the results of stress calculations. It may be desirable in some cases to replace a one-piece die-insert with axially split die-insert or transversely split die-insert.

(c) Die Material. The third aspect of design is concerned with the selection of suitable materials for dies and stress rings. The questions of strength properties, wear resistance, die life and economics of the process have to be dealt with.

The computations of shrink-fit assemblies are based on the theory of an infinitely long hollow cylinder (Lange, 1985). This assumption has been used in industry with good success for the design of dies under high pressure. A die assembly with two shrink rings and the guidelines for the stress limits are shown in Fig. 16.

For this case, the properties of 501 steel were used. The yield strength of 501 steel under full anneal is 30 ksi. The computed values of the parameters using the above guidelines are as follows.

d_1 = 2.2 inch
d_2 = 4.6 inch
d_0 = 10.0 inch
z_1 = 0.015 inch
z_2 = 0.039 inch

where z_1, z_2 are the absolute interferences at d_1, d_2 respectively.

Considering the high stresses it is recommended to use a punch of M4 steel with TiN coating. The die insert should be made from M4 steel and shrink rings from H13 steel.

11 Experimentation to Manufacture the Nozzle

The tooling designed in the previous section was manufactured at a cold forge shop as per the detailed drawings of each component of the die set assembly. Starting billets of 501 steel were prepared. These were lubricated with a phosphate film. The part was successively manufactured on a multi-action hydraulic press from one stage to the next according to the designed sequence of operations. The material flow was studied for each stage of the forming process. The final dimensions of the part and the desired material flow was achieved with the

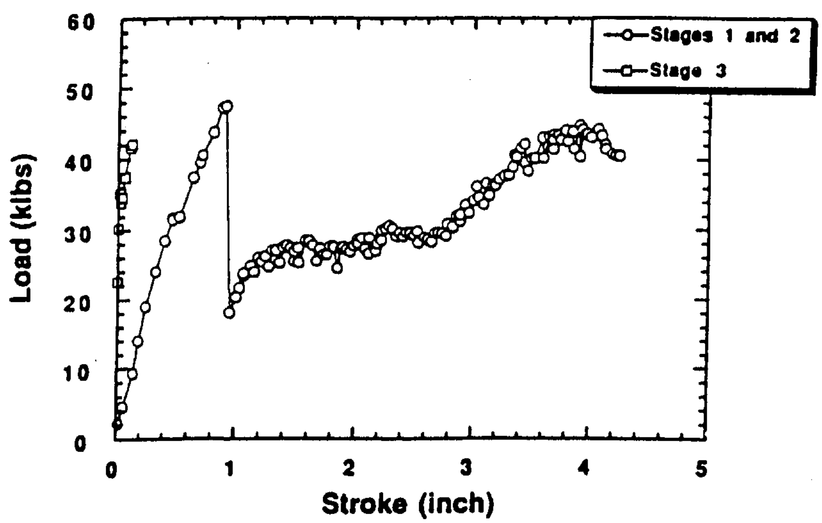
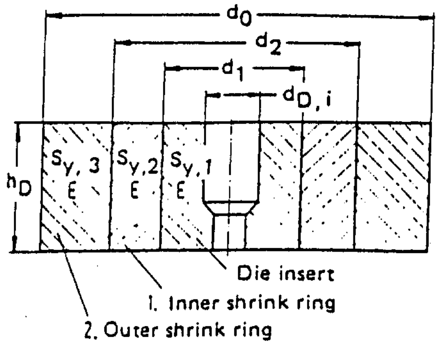


Fig. 15 Load-stroke curve for the modified sequence



Inner Pressure p_i, N/mm^2 (ksi)	Number of shrink rings	Diameter ratio d_o/d_i	Approximate value for the interface diameter
To 1000 (to 145)	0	4-5	-
1000-1600 (145-230)	1	4-6	$d_1 = 0.9\sqrt{d_o d_i}$
1600-2000 (230-290)	2	4-6	$d_i{:}d_1{:}d_2{:}d_o =$ 1:(1.6-1.8):(2.5-3.2):(4-6)

Fig. 16 Guidance values for doubly shrunk die for extrusion (Lange, 1985)

cold forming sequence. An analysis of the manufacturing process showed that the lubrication of the part is very critical. The phosphate coating did not last the entire sequence of operations. Relubrication was necessary at the end of each stage because large deformations cause the breakdown of the lubricating film. Since this was a concept demonstration, lubrication of billet would need further process development in order to eliminate relubrication after each stage to make the process more economical. It was also observed that the ejection of the part is an issue which would need further development for successful large volume production.

12 Conclusions

This research work has shown that simultaneous engineering can be effectively used in the industry for process development and tooling design to manufacture parts with complex geometries. The study presented here has shown that computer aided sequence design combined with finite element analysis can be used efficiently to design and develop cold forming processes for making fuel system parts.

The use of FORMEX to design a sequence for cold forming proved to be very useful. In the hands of an experienced designer, it can result in valuable savings of time, money and effort. Analysis with the finite element code DEFORM gave valuable information about the forming process. The results of the initial sequence gave a preliminary insight into the punch pressures (by using the interpolation program TRANSFER), loads required and material flow for forming the nozzle. The initial sequence was modified to obtain a more realistic and practical punch pressure distribution, which was a cause for serious concern. The finite element modeling also showed that the innovative multi-action process for cold forming in the final stage of the sequence can help reduce the loads and punch pressures by a large degree.

DEFORM proved very useful in punch stress analysis. Since the punch is slender and long, we have to use punches made of tool steel. A carbide punch will be brittle for this application. It is recommended that the punch be made of M4 steel with TiN coating and die insert of M4 steel.

During the finite element simulation of the forming process, the pressures obtained would be more than those that would be developed in real case because in the actual manufacturing process the punch and die deform elasticity. Also, the pressures and loads obtained from FORMEX were lower than DEFORM simulation because FORMEX gives the average values of pressures, loads and strains.

The experimentation carried out to manufacture the part with the multi-action sequence design arrived at in this study has proved that cold forming is a feasible process for such complex parts. The manufacturing process needs some more development in the industrial world.

13 Acknowledgments

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