COMPUTER AIDED ENGINEERING IN FORGING

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Industrial Summary

Global competition requires that the forging industry utilize practical and proven computer aided engineering (CAE) technologies for rapid and cost effective process design and die manufacture. The CAE has been an integral part of forging process design to analyze and optimize the metal flow and conduct die stress analyses before trial runs. For more than a decade 2-D finite element process simulation has been the state-of- the-art, and presently 3-D finite element simulation is gaining wide acceptance in industry to address asymmetrical 3-D forgings. Examples of CAE in microforming, orbital forging, clinching, crimping, net shape forging of gears with helical teeth, and tool life enhancement are presented to illustrate the present practical and ongoing development in improving the simulation efficiency.

1. Introduction

Global competition requires that cold forging industry utilize practical and proven computer aided design (CAD), computer aided manufacturing (CAM) and computer aided engineering (CAE) technologies for rapid and cost effective process design and die manufacture. Recently, finite element (FE) simulation software has become an integral part of forging process design to analyze and optimize the metal flow and conduct die stress analysis before conducting forging trials.

The main goal of simulation in manufacturing process design is to reduce part development time and cost while increasing quality and productivity. For instance, in cold forging, process simulation can be used to develop the die design and establish process parameters by a) predicting metal flow and final dimensions of the part, b) preventing flow induced defects such as laps and c) predicting temperatures (warm forging operations) so that part properties, friction conditions, and die life can be controlled. Furthermore, process simulation can be very beneficial in predicting and improving grain flow and microstructure, reducing scrap, optimizing product design and increasing die life. Two-dimensional FE simulation has been state-of-the-art in cold forging process design for more than a decade. With asymmetrical complicated parts, the use of three-dimensional FE simulations is a must. During recent years, 3-D simulation has also gained widespread acceptance in industry. Improvement in computer algorithm efficiency and user interface development have resulted in simulation becoming both robust and practical in a wide range of applications **[1].** Fig. 1 illustrates the role of FEM in forging process design by means of a block diagram **[2].**

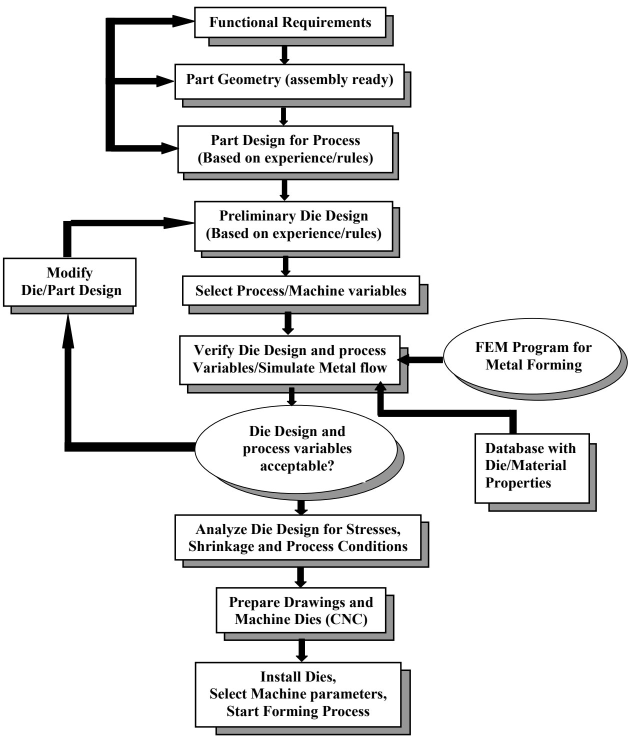


Fig. 1: A flow chart illustrating forging process design **[2].**

2. Input variables in the FEM models

The accuracy of FE process simulation depends heavily on the accuracy of the input data, namely, a) flow stress as a function of temperature, strain, strain rate and microstructure, b) friction characteristics at the interface.

2.1 Workpiece and tool material properties

The stress-strain relation of materials, commonly referred to as the flow stress curve, is usually obtained by the cylinder compression test. To be applicable without errors or corrections, the cylindrical sample must be upset without any barreling (Fig. 2a) i.e., a state of uniform stress must be maintained in the sample at all times during the test. Use of adequate lubrication prevents barreling to some extent. However, in practice, barreling is inevitable and procedures for correcting flow stress errors due to barreling may be necessary.

Fig. 2a shows a sample that was upset to 62 % reduction (true strain of 0.96). This sample shows significant barreling implying that the lubricant applied was ineffective at this high level of strain. The failure of the lubricant is evident by the two different regions (shiny and non-shiny areas) depicted on the surface of the sample (Fig. 2a). In general, for process modeling of precision forging, the experimental flow stress curves were found to be reliable only up to a strain level of 0.5 **[3].**

One way of correcting the flow stress, or determining approximately the error magnitude at high strain levels caused by inadequate lubrication (barreling), is to simulate the compression process by FEM using various friction factors (Fig. 2c) **[3].** By measuring the amount of barreling (Fig. 2a) and comparing the experimental data with FEM predictions it is possible to obtain more reliable flow stress data at higher strain levels. This method, called inverse analysis technique, has been used to determine simultaneously friction and stress/strain data using a ring test. Details on inverse analysis are discussed in section 2.3.

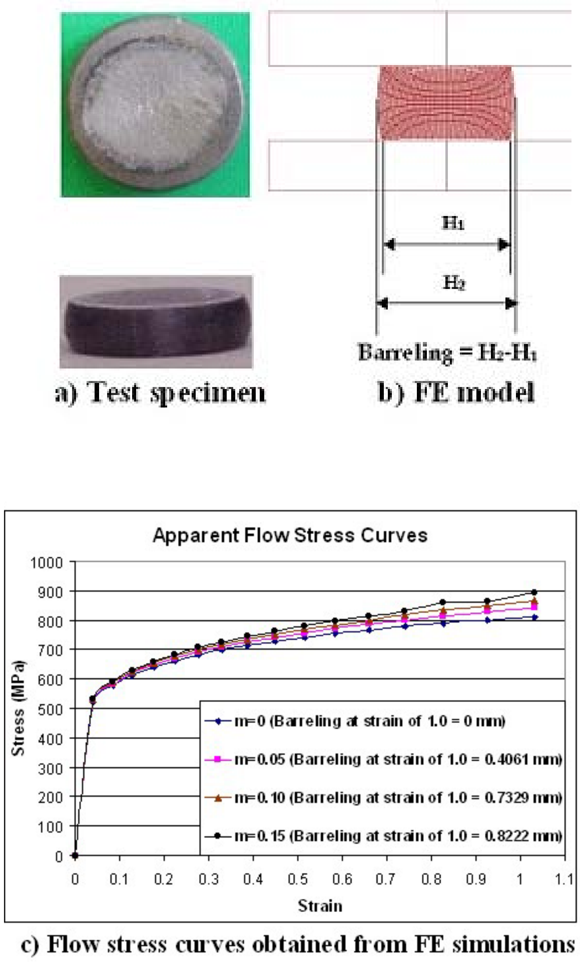


Fig. 2: Correction of flow stress data obtained from a compression test **[3]**

Attention should also be given to other sources of flow stress error determined through compression tests such as: a) variation in coil material properties, b) specimen preparation, c) surface defects, d) parallelism of platens, and e) specimen size.

Though in most FE simulations the tools are considered rigid, this assumption may not hold good for complicated forgings with tight tolerances, particularly in microforming applications. Hence, depending on the part complexity, elastic-plastic properties of the tools/dies become an important component in the simulations

2.2 Interface friction

Friction coefficient is another important input in the FE model. The friction value may vary from cold to hot forging processes. Prior to process modeling one need to know what lubrication system will be used in production. For the case of cold forging of steel zinc phosphate coating based lubrication system is a typical lubrication with exception of simple forging processes. There has been a growing concern in the use of Zinc phosphate coating based lubricant because the coating contains toxic substance, harmful to human being. Efforts are being made to develop new lubricants.

In the evaluation of new lubricants, reliable tests that emulate process variables occurring in forging operations are of paramount importance. A number of tests have been developed for lubricant evaluation for cold forging. Literature review of these test are given elsewhere [4, 5, 6]. A good test, however, should emulate realistic process variables occurring in forging operations. ERC /NSM has tested several environmentally friendly lubricants for replacement of zinc phosphate coating based lubricant using double cup backward extrusion test (Fig. 3).

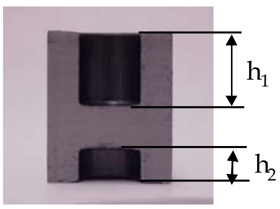


Fig. 3: Specimen showing the cup heights after the double-cup extrusion test.

The principle behind this test is that the difference in the cup height is an indication of lubricity. If the cup height ratio is equal to one then friction is equal to zero.

Fig. 4 shows the friction values obtained from four tested lubricants. MEC Homat was found to be the best among the four tested lubricants, with a friction factor of about 0.035. MCI and Daido also performed better than zinc phosphate lubricant. Hence, these lubricants can replace zinc phosphate for parts whose surface enlargement is within 500%. The 500% refers to the surface enlargement induced in the double cup backward extrusion test used in evaluating the lubricants.

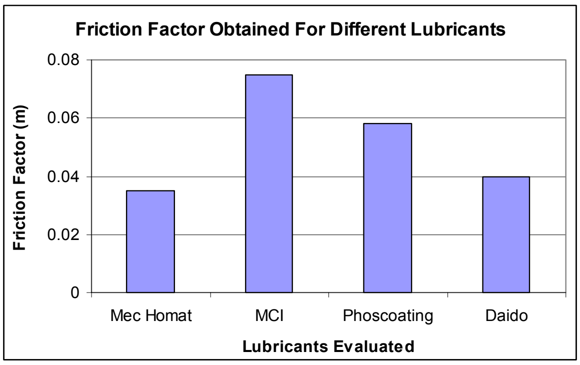


Fig. 4: Ranking of the lubricants based on the friction factors obtained.

2.3 Simultaneous determination of friction and flow stress by inverse analysis

There is a concern in the reliability of flow stress determined by compression test, particularly, when determining flow stress at elevated temperature or when a good lubricant to prevent barreling of the specimen is not available. Due to the rapid advancement in computer technology, the use of inverse analysis, which combines experiments and FEM seem practical to determine material parameters and other variables that can be simulated with FEM [7,8].

ERC/NSM has developed a method based on the inverse analysis that can simultaneously determine flow stress and interface friction from the ring compression test experiment (Fig. 5).

The inverse analysis is aimed at determining the material parameters used in flow stress equation and the friction factor with an objective function of minimizing the difference between experimentally measured data and the simulation results. For example in Fig. 6a, Load-Stroke curves (experimental and simulation) will be minimized to determine material parameters. While, in Fig. 6b, minimization of ID-Stroke curves will be carried out to determine the interface friction. The procedure for simultaneous determination of flow stress and friction in given in Fig. 7[**7**].

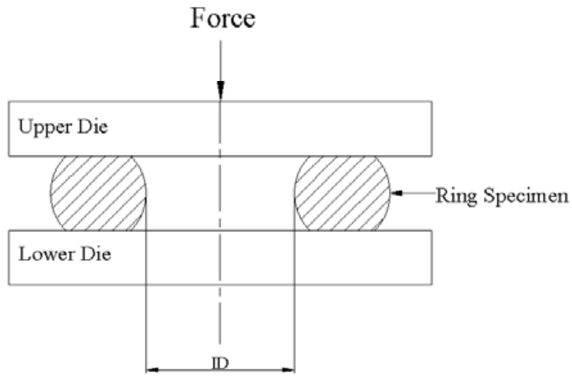


Fig. 5: Schematic diagram of the ring compression test.

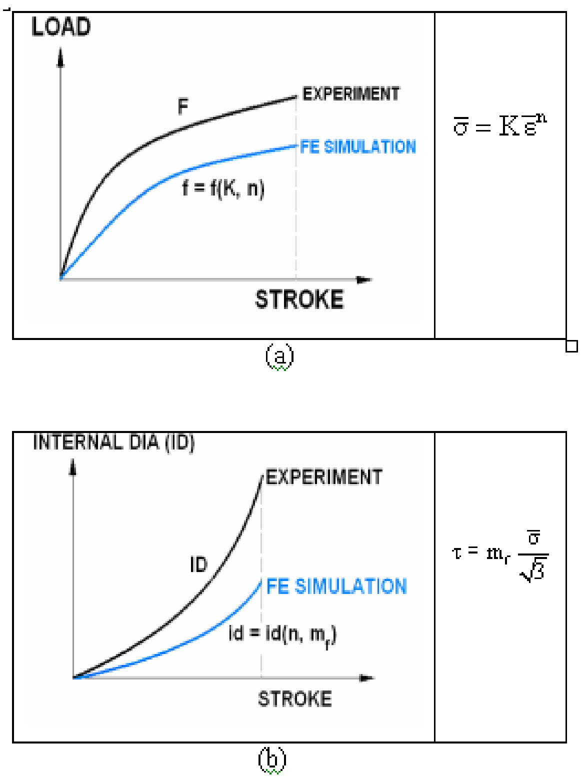


Fig. 6: Methodology for simultaneous determination of friction and flow stress by inverse analysis.

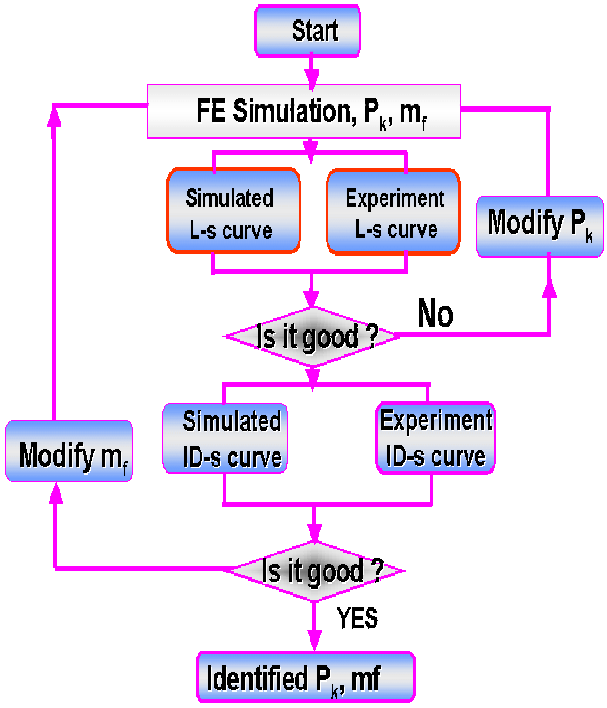


Fig. 7: Flow chart of inverse analysis procedure.

3 Application of CAE in Precision Forging - Case Studies

The most effective and mature applications of simulation in forging are a) development of forging sequences, b) die stress analysis, c) solving problems related to an existing manufacturing sequence, etc. FE process simulations are also used for quotation of new jobs by forging companies **[3].**

A number of forging companies producing complex near net shape parts have started using 3D finite element analysis (FEA). Examples of complex 3D forging operations that can presently be handled with ease includes, orbital forging, microforming, clinching, heat treatment operation etc.

3.1 Advanced orbital forging simulation

Orbital forging is a very unique process with a complicated die movement that can be used to reduce axial load requirements for axisymmetric or near axisymmetric forging operations. At the ERC/NSM, orbital forging simulations were conducted to study and develop a robust assembly process of an automotive spindle and an outer ring. Fig. 8 shows the simulation progression, which considers elastic and plastic deformation, residual stresses, and quality of assembly.

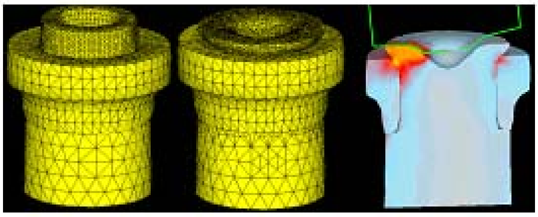


Fig 8: FE simulation of orbital forming (FE model and Stress distribution)\

3.2 Microforming

The trend in miniaturization allows the production of cold forged parts with dimensions less than 1 mm range for electronics and biomedical applications. These parts are currently produced by 3D etching and other metal removal processes. Microforming is a potential process for mass production of net shape/near net shape micro components. However, for microforming to be cost effective and competitive a comprehensive knowledge pertaining to the following factors is needed: a) scale effects/microplasticity b) effect of microstructure on the process, c) relative stiffness of the tooling and d) process control and capability.

With the aid of FEM, the inter-relationships between these variables can be studied so as to provide guidelines for developing microforming processes. In cooperation with industry the ERC/NSM has developed a microforming process for making surgical blades. Fig. 9 shows an example of 3D FE simulations for a surgical blade with initial blank thickness of 0.1mm and final edge thickness of 0.01mm **[9].**

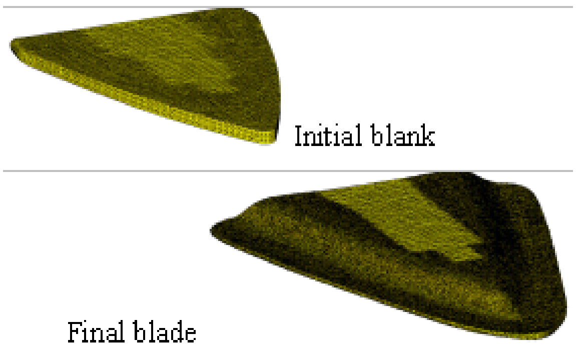


Fig 9: Microforming of surgical blades (Blank thickness = 0.1 mm; Final blade thickness = 0.01 mm) [9].

Due to high surface to volume ratio in microforming process, friction becomes even more important than in conventional forging. Effects of miniaturization on friction have been investigated by using the double cup backward extrusion test with oil as a lubricant (Fig. 10). Comparisons between experiment and simulation show that friction effects increase with a decrease in size of the specimen. The friction observed for a 1mm diameter billet was 4 times that for a 4 mm diameter billet.

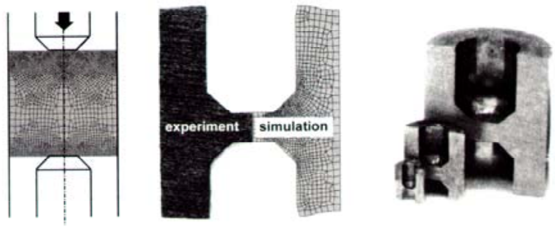


Fig 9: Double cup extrusion test for determination of friction conditions in microforming [10].

3.3 Clinching Simulation

Clinching is a joining technique for fastening sheet metal components. Sheet metal is pushed into the die cavity by a punch and a leak proof mechanical interlock is formed. There are also many leak-proof joint that require hard fasteners to be attached to a sheet metal part **[11].** Depending on the size of the fasteners and the required strength of the joint, the clinching design may be extremely difficult as the process window for clinching may be very narrow.

With the aid of FEM ERC/NSM successfully designed a clinching process for an airtight system for a company. As seen in Fig. 11 iterative FE simulations were conducted to obtain a better preform where they finally clinched to the required pull out load. The stages followed in the clinch joint development were:

- FE simulation of preform geometries. Forming of a dimple [Fig 11a] was simulated as a precursor to the clinching operation thereby providing strain history and work hardening. Three preform punches were used to obtain the final perform shown in Fig. 11b.
- FE simulation of fastener clinching joint. A single punch was used to make the joint

[Fig.11c]. Simulation results showed that the preform geometry has a large influence on how material forms around the fastener and fills the undercut.

- FE simulation of pullout. The pullout simulations provided the required fastener removal force.

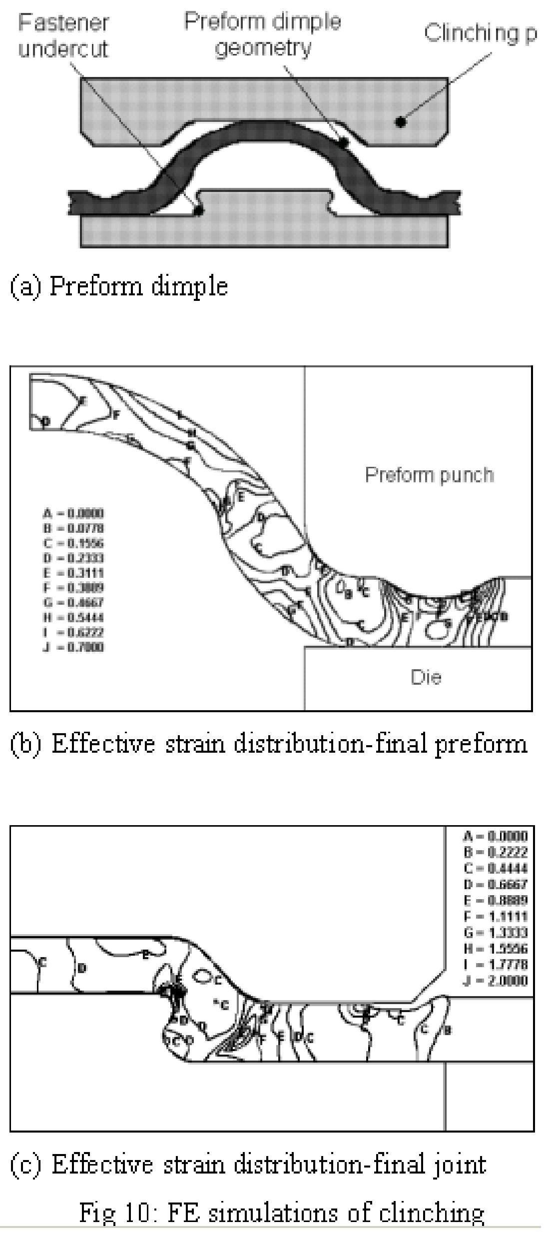


Fig 10: FE simulations of clinching

3.4 Hydraulic crimping

The design of crimping processes for assembling tubular components relies mainly on experimental trial and error methods, which prove to be very expensive and time consuming. Process simulation using advanced FEM provides a valuable means for evaluating and optimizing tool and process variables. A typical hydraulic crimping process is composed of a rod that is press fitted into the tube to a predetermined depth, and then a hydraulically pressurized rubber crimper pushes the casing into two grooves machined on the rod forming the assembly (Fig. 12).

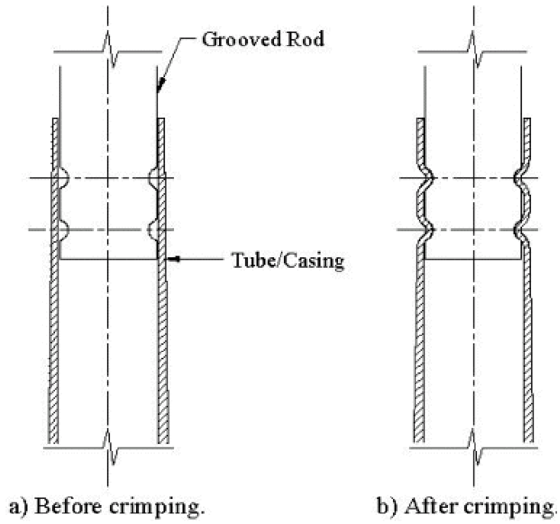


Fig. 12: Rod – casing assembly before and after crimping

The crimp quality is critical to the final performance of the assembly. The quality of the crimping operation is evaluated by a pullout test, which measures the force required to disassemble the grooved rod from the casing. A variation in the geometrical properties of the crimp may cause variations in the performance desired from the assembly. Though a failed casing rarely occurs during pullout testing, when it does, it is normally near the crimp.

FEM was used to investigate the influence of the following variables upon performance of the crimp assembly.

- The material properties of the casing prior to crimping. Since the casing undergoes a series of forming and heat treatment operations, its properties are altered by the time it reaches the crimping stage.
- The optimum range of interference fit between the rod and the casing.
- Alignment between the rod and the casing, which gives the maximum pullout force

without damage to the casing in the pullout test.

- The effect of the sealant used during assembly on the quality of the crimp. This effect was considered by using different coefficients of friction (μ) during crimping and pullout.

Two alignments were chosen for the press fitting process to study the effect of the depth to which the rod/bullet is inserted on the crimping and pullout force. This consideration addresses the misalignment errors that may occur during the press fitting stage. Flow stress of the casing was estimated from the hardness of the casing [15]. Due to variation of hardness from several bullet cases tested, maximum and minimum flow stress curves were used in the FE analysis.

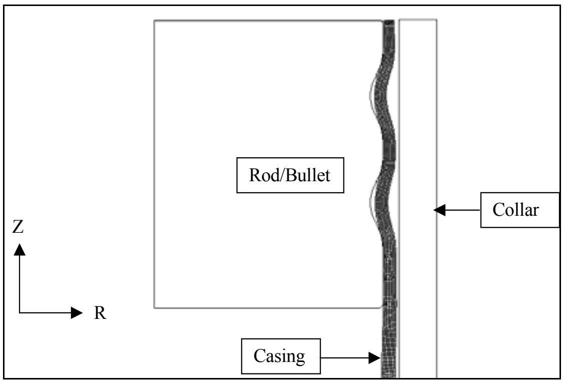
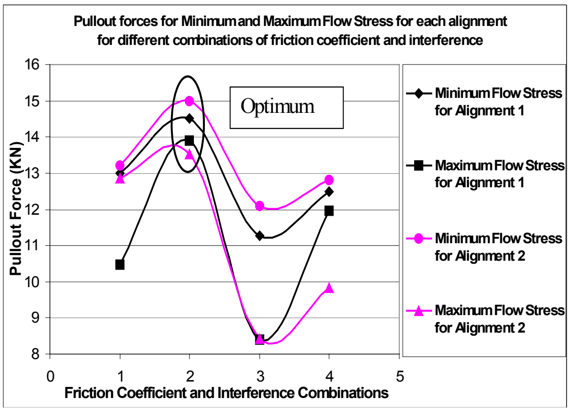


Fig. 13: FE model for the rod pullout test.



Combination	Friction Coefficient (μ) and Interference Fit
1	μ = 0.45; Maximum Interference Fit
2*	μ = 0.45; Minimum Interference Fit
3	μ = 0.2; Maximum Interference Fit
4	μ = 0.2; Minimum Interference Fit

**-Optimum combination.*

Fig. 14: Optimum process parameters for the rod crimping process.

From the FE results shown in Fig. 14 it can be observed that the pullout force values for the two alignments with the combination of minimum flow stress, minimum interference fit and maximum friction yields the maximum pullout force values [15].

3.5 Hot Forging Simulation of Aerospace Components

Commercial finite element (FE) simulation software, such as DEFORM-3D, has found wide application in the aerospace and automotive sector for analyzing structural components as well as simulating forming operations. Fig. 15 shows the forging sequence of an aircraft wheel simulated using DEFORM-3D. The main objectives of this study were to use DEFORM-3D to a) obtain the temperature and strain distribution during forging, b) study the metal flow, c) study die filling and conduct die stress analysis to verify the die design.

The flash generated in the blocker stages is removed in practice either by trimming or by means of a blowtorch. This is an important aspect of the forging sequence, which had to be taken into consideration while running the simulations in order to maintain an appropriate volume of material in the dies. The Boolean capability of DEFORM was used to remove flash between blocker stages.

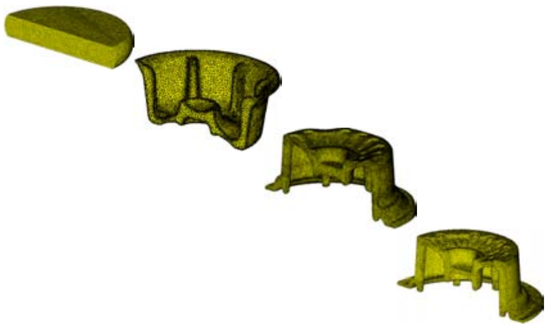


Fig 15: Aircraft landing gear wheel (Wheel diameter = 560 mm, Height = 216 mm; No of elements = 60,000), by ERC/NSM [12].

3.6 Tool life in cold forging of bevel gears

Numerical process simulation and a subsequent set of stress analyses were used to predict the pressure distribution at the material-die interface and thus improve the design and service life of a punch in cold forging of bevel gears (Figs. 16, 17, and 18). The geometry of the highly stressed punch is seen in Fig. 14. Using the interface pressures as input, the ABAQUS code was used for the elastic-plastic analysis of the punch stresses. Very high pressures were obtained at the lower punch corner and in the upper fillet radius. By varying the punch geometry, after a few iterations, it was possible to reduce the peak stresses and distribute the punch load more evenly (Fig. 17). As a result of these geometric changes, the punch life was increased by a factor of 6 to 8.

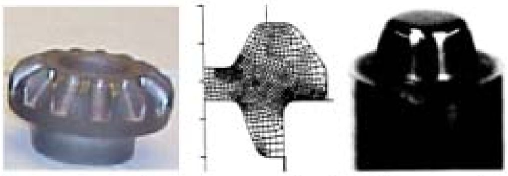


Fig 16: Bevel gear, FE model and the punch used to forge the gear **[13].**

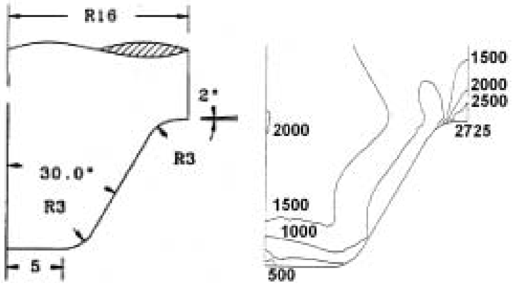


Fig 17: Stress contours in the punch before geometric modifications.

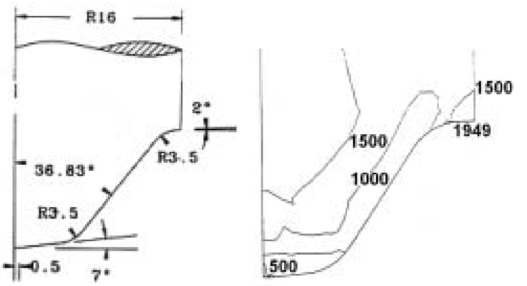


Fig 18: Stress contours in the punch after geometric modifications.

3.7 Design of Power Steering Pinions and Inner Races

Net shape forging of power steering pinions with helical teeth, helical gears and inner races present a great challenge. However, the use of commercial 3D finite element software in process development has drastically reduced the production costs by eliminating multiple trials and at the same time has improved part quality, tool life and geometric complexity of forgings. Fig. 19 shows the application of FE simulations in the design and development of the helical extrusion process for manufacturing the pinion shown. The advantages of using FEM to simulate and hence design the optimum process were [14]:

- Obtain a better drive feeling.
- Generate the tooth profile freely.
- Establish an iterative technique for die and process design as well as heat treatment.

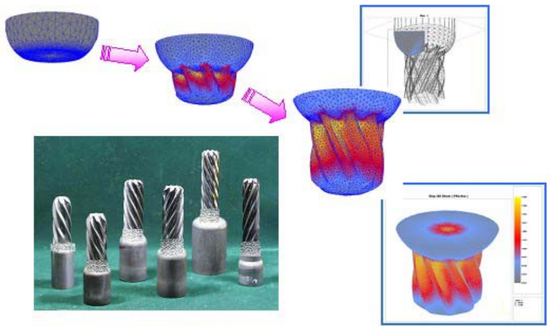


Fig 19: Development of steering pinion with the aid of FE simulation [14].

Fig. 20 shows the simulation of cold forging of the inner race, which is a part of the constant velocity joint assembly. The raw material is a round bar, which is forged in an enclosed die set. Thus, accurate control of the billet volume is essential. This can be checked via FE simulations in addition to the metal flow and die stress analysis. The advantages of simulating this process were **[14]:**

- Obtained net-shape on the grooves, thus eliminating the costly grinding process used in the finishing stages.
- Establish an iterative technique for die and process design as well as heat treatment.
- Secure forging accuracy without using a special press.

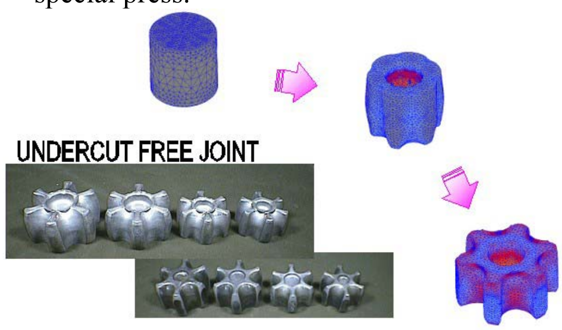


Fig 20: Cold forging of the inner race of a CVJ **[14].**

3.8 Integrated heat treatment analysis

Advanced FE process simulation tools like DEFORM 3D are now capable of studying the residual stresses after heat treatment. This includes modeling of microstructural effects, thermal mechanical influences and modeling of the quenching process for cracking and distortion [1]. An example of heat treatment simulation is shown in Fig. 21. Dark regions show the volume fraction of martensite transformation and light regions indicate a mixture of bainite and pearlite [1].

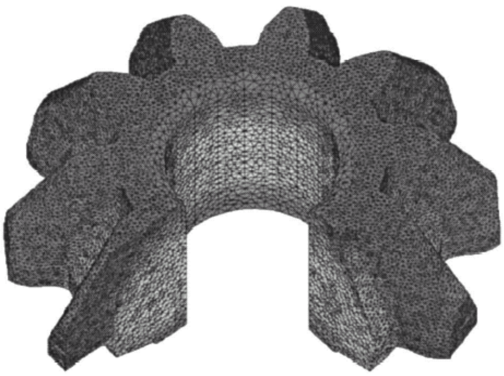


Fig 21: Heat treatment simulation of a bevel gear [1].

4. Summary and Conclusions

The numerical simulation of forging processes with FEM based codes assists the forging engineer in establishing and optimizing process variables and die design. As a result, process development efforts and cost can be reduced. To survive in the global market economy, the forging industry needs to utilize practical and proven CAE technologies for rapid and cost effective process design and die manufacture. Two-dimensional FEM is now widely used in solving industrial problems. The rapid advancement in computer technology and algorithms has drastically reduced the computation time, thus making 3D FEM cost effective. The 3D FEM is now gaining wide acceptance by industry for solving forging problems related to complex asymmetric parts.

The use of CAE will continue to grow in the forging industry. However, to ensure that the forging industry maintains its competitiveness with other manufacturing processes, more effort is needed in areas such as:

- Accurate determination of input data for FE models (interface friction and material properties).
- Further improvement in the FE codes to handle complex 3D geometries in both non-isothermal and isothermal simulations.
- Parallel processing computer systems so that large 3D simulations can be cost effective.
- Development of FEM experienced based knowledge data banks to aid in quick design of process sequences.
- Optimizations of preform die geometries.
- Training for engineers to equip them with relevant knowledge in CAE and related disciplines so that they are capable of interpreting complex forging processes into mathematical/FE models. Thus, reliable optimization of processes can be enhanced.

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