INTEGRATED PRODUCT AND PROCESS DEVELOPMENT USING FEM-BASED MODELING OF OPEN-DIE FORGING OPERATIONS

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ABSTRACT

This paper describes the technologies and human factors involved in the successful development of an FEM-based computer system to be used to model the open die forging process of a steel company. An overview of the company environment is described along with the markets served and the typical product development cycle. Alternative methods for modeling open-die forging are discussed, and the advantages of FEM analysis using state-of-the-art computer hardware and software are presented.

This FEM-based modeling system was developed in partnership with the Lehigh University Enterprise Systems Center and a private sector company with partial support from the Commonwealth of Pennsylvania. This partnership is described and the resulting methodology for using FEM is explained. Several case studies are presented. These include use of the system for 2D analyses in head forming product development and 3D analyses in cogging operations.

INTRODUCTION

The company involved in this project serves the segment of the forging market requiring larger-sized forgings. This segment includes: 1) the metals market with both hot and cold mill work rolls and backup rolls; 2) the general industrial market with shafting, die blocks, etc.; and 3) the pressure vessel market with formed heads with and without integral nozzles and special shell forgings with integral nozzles. The typical maximum ingot weight involved is 261 tons (290 US tons) and 3302mm (130") in diameter. Manufacturing capabilities include a 9,000 (10,000 US) ton press, and complete machining, heat treatment, and testing facilities.

Historical Product/Practice Development - For many years, new products and practices were developed in this company through large-scale experiments and trials on production forgings. Both large scale pre-production and production trials of products can cost tens of thousands of dollars. If production forgings are used for development work, both dollars and delivery are at risk. To minimize these risks, changes in practices must be done in a very conservative manner. Both of these alternatives for development are very time consuming. Today's

competitive marketplace does not favor those who are slow to respond to market changes and inquiries.

Modeling of Open-Die Press Forging - During the last 15 years, in an effort to reduce developmental lead times and cost, the company's engineers have worked with a variety of resources to develop and apply modeling techniques to the forge shop. These modeling tools which often involve the heating, forging, and cooling of steel have afforded the freedom to try many new ideas easily, cost effectively, and with no risk to product quality. They have been used to develop new products and methods, as well as refine existing ones. The major focus for these efforts has been the modeling of the open-die forging process itself using both physical and computer modeling techniques.

PHYSICAL MODELING

This company's research department has been among the leaders of metal-processing modeling efforts in the country. Their research laboratory features a world class physical modeling facility. In work carried out at this laboratory, both plasticine and lead have been proven to be excellent tools in simulating the working of hot steel [1,2,3]. When processed under strictly controlled conditions, these physical-modeling materials can provide, at room temperature, information and insight into the material flow, stress/strain behavior, and forming loads for steel at hot-working temperatures [3,4,5,6]. A close working relationship between the forgemaster and the laboratory engineers has made this relationship the cornerstone of numerous modeling efforts in both the plasticine and lead modeling media [7].

COMPUTER MODELING

For many years, various computer-based heat transfer models for the mainframe and PC were used in the company to model heating and cooling processes. These models have proven to be accurate and helpful in predicting temperature curves but cannot predict the deformation in a forged product. Several years ago, a strategic commitment was made to expand the development and use of computer modeling technologies as an aid to improving its operations. During initial feasibility studies it became apparent that certain trends had emerged making FEM modeling of forging attractive as a cost-effective, stand-alone processing development tool. For example, improved software compilers and convergence algorithms had led to modeling codes that were fast, cost effective, and user friendly. Better pre/post-processing software tools had to become available to facilitate the visualization and animation of time-dependent data generated from computer models. Work had been conducted on the characterization of the deformation and heat transfer properties of common forging materials. Lastly and most importantly, the tremendous recent progress made in the price/performance ratio of computer hardware required to run computation-intensive forging codes in a timely manner contributed to making FEM modeling an ideal development tool.

In view of the these trends, a decision was made to partner with a university familiar with this technology and to apply for a state-funded grant to specify and implement an FEM-based modeling system. The university would provide expertise in CAD, FEM and computer science

in the selection of hardware and software packages to make up the proposed system. A grant request was submitted to and approved by the state.

PROCESS IMPROVEMENT OBJECTIVES

Initial design guidelines that were developed by the company and university were:

- Maintain lowest possible initial and recurring costs.
- Usable by personnel who are not FEM/CAD/Unix experts and whose time is not dedicated 100% to CAD/FEM efforts.
- Adaptable/usable hardware that can be used in other applications.
- Leverage existing skills wherever possible
- Maintain flexibility for future additions/changes.
- Capable of multiple-pass, 3D cogging (rotor forging) analyses.

To help meet these guidelines, additional design philosophies were:

- Maximize use of low-cost, PC-based hardware and software
- Leasing hardware/software as opposed to outright purchase.
- Modular approach to both hardware and software functionality.
- Using multi-purpose, network-based peripherals.

After considerable study, a 2D/3D FEM bulk deformation process modeling package called ANTARES™ (described in a subsequent section) was selected as the deformation modeler. Installation of the system was completed during the second quarter of 1996.

MODELING SYSTEM HARDWARE

The hardware utilized includes a Unix-based workstation, two Intel-based PC's, a high-speed network server, and high-density storage peripherals. The Unix workstation was selected for its high floating-point performance. The server ties all the computers together for data management and transfer. Tape drives and other mass storage units are present to back-up data from old analyses.

MODELING SYSTEM SOFTWARE

CAD Modeling Software - AutoCAD R13-c4 from Autodesk, Inc. was selected as the CAD package to create 2D tool and workpiece geometries for 2D simulations and the 3D solid models required for 3D simulations.

Pre-Processing and Meshing - FEMAP™ with Advanced Meshing Module (AMM) from ESP, Inc. was selected for pre-processing and meshing of the CAD models prior to an FEM run (Figure 1).

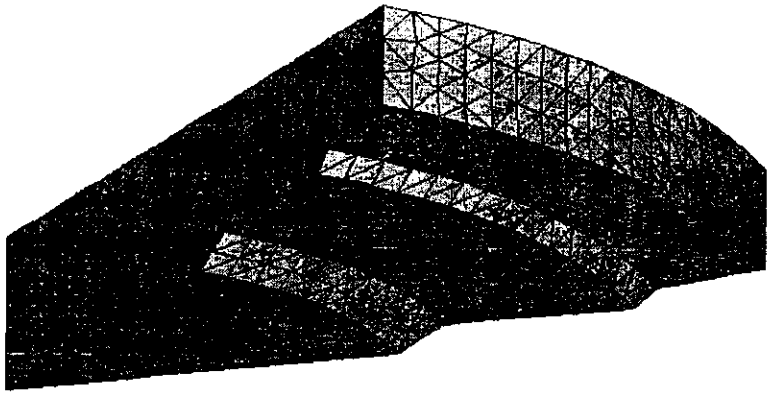

Figure 1: Segment of a Forging Blank Generated with AMM

FEM Solver - ANTARES™ is a special purpose software package developed and marketed by UES, Inc. for modeling 2D and 3D bulk process deformation [14,15].

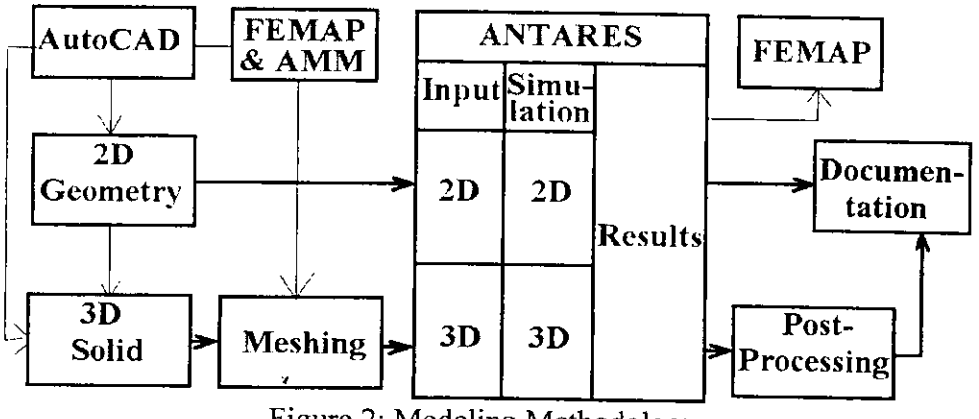

Figure 2: Modeling Methodology

For 2D simulation, the initial model geometry can be done in ANTARES or other CAD software. Using other CAD software requires the file to be saved in a universal format, such as IGES. ANTARES can then create a finite-element mesh from the geometry and perform an analysis (Figure 2).

For 3D simulation, the initial solid model has to be done using third party software and then inputted to ANTARES via a universal file format. First it is sent to FEMAP to create a mesh using AMM. The mesh can then be imported to ANTARES (Figure 2).

APPLICATIONS AND CASE STUDIES

Some specific examples of use of the FEM Modeling System for problem solving and/or new product development are as follows:

2D Axisymmetric Simulations

Head Forming - This example illustrates how an improved forging blank design was developed for a formed-head closure. Figure 3 shows a section view of a forging blank.

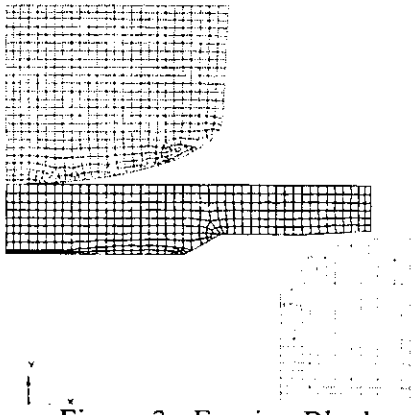

Figure 3: Forging Blank

The modeling methodology used was as follows. computer models of the tool set (top die and bottom die) and the first iteration of the forging blank were generated using AutoCAD. The blank and tool geometries were imported via file format translator into ANTARES. A 2D-axisymmetric simulation was possible due to the symmetry of the dies and workplace. Hydraulic press parameters, materials for the objects, the lubricant to be used, and the process parameters, such as the initial temperature conditions as well as contact boundary conditions, were assigned to the blank and dies. The 2D-axisymmetric geometries were meshed in ANTARES and submitted to the ANTARES 2D-axisymmetric FEM solver. An area of underfill, Figure 4, was predicted by the simulation results. A second iteration, an improved blank design, was designed with CAD. Additional blank thickness was added in the underfilled area, and the overall diameter on the blank was reduced. The die design was not modified. The simulation was then repeated with the improved blank geometry.

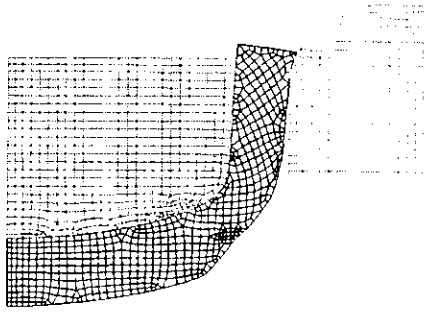

Figure 4: Underfilled Forging

The improved blank design resulted in a better forging more dimensionally suitable for heat treatment and final machining. The area of underfill was eliminated and the cut-off waste on the

top of the circumference was greatly reduced. Numerous other 2D axisymmetric simulations have been conducted as part of process and product development efforts. A brief overview of some of this work is as follows:

Punch Forming with Flattening - Figure 5 shows a case study of a two-stage, punch-then-flatten operation. In this study, FEM analysis was conducted to help predict the severity of an edge curl-up condition that was expected to occur in the punch stage, and the ability of a subsequent flattening operation to correct the curl-up. The trends predicted by the model agreed well with those seen in real-world production runs of similar products. A deformation strategy was planned and successfully executed in production.

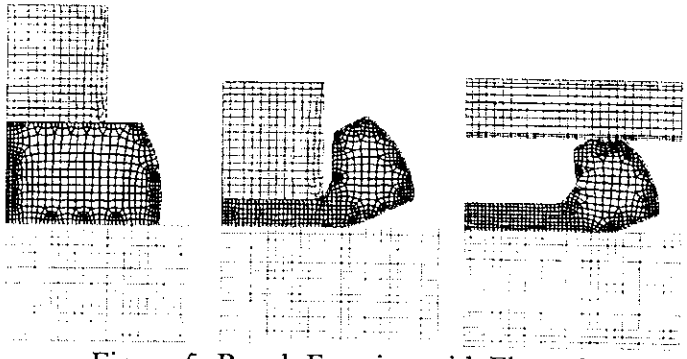

Figure 5: Punch Forming with Flattening

Ingot Upset Die Design - Figure 6 illustrates the FEM modeling of an upset operation on a large ingot. Modeling runs were carried out to assess the effect of varying the ingot "chuck" length relative to the height of the ring die on consolidation of voids in the "dead zone" of the ingot. The study suggested areas for potential improvement so field evaluations of a modified design have been initiated. Preliminary results are encouraging, although more data is required. Additional field evaluations are planned.

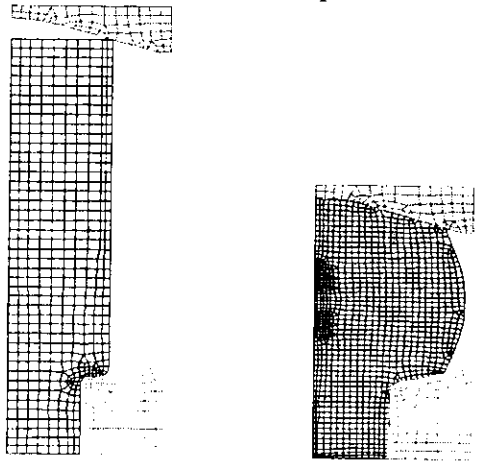

Figure 6: Ingot Upset Die Design

3D Non-Axisymmetric Simulations --- Rotor-Forging

Figure 7 shows a 3D-simulation strategy for rotor cogging processes, i.e. forging of a large ingot into a rotor. This application is difficult to model because it consists of multiple deformations along the body of the ingot with the ingot being rotated and/or translated after each stroke of the press.

In a simulation of this nature the workpiece deformation and stresses are of primary interest, not the dies. Using CAD, a solid model for the workpiece and skin models for the dies are built. FEMAP/AMM is used to discretize the boundary surfaces using triangles. The workpiece and die surfaces mesh is imported into the pre-processor of ANTARES™. The boundary conditions, mesh specifications, and simulation control parameters are assigned. Special keyword files are written on to disk to specify the details of the 3D simulation.

In this simulation, there are four deformation strokes along the length of the ingot in each pass. After finishing one pass down the body of the ingot, the ingot is rotated 90 degrees or 45 degrees around its longitudinal axis and translated back to the original position. This sequence is repeated again and again until the necessary passes have been completed. During FEM simulation of this type of forging operation, the FEM results of each press stroke are automatically set up to be transferred as input to the next run.

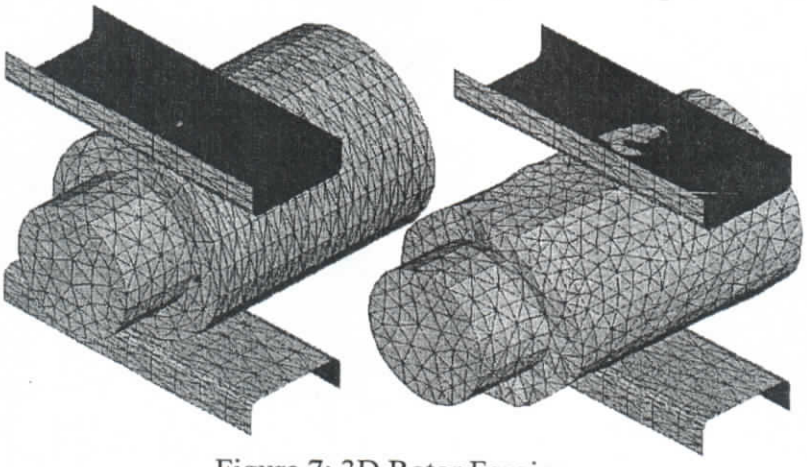

Figure 7: 3D Rotor Forging

Good progress has been made in simulating this type of operation, and soon it will be possible to assess the effect of various drafting strategies on void consolidation during rotor forging.

SUMMARY/CONCLUSION

A low-cost FEM based computer system has been developed and implemented for modeling open-die forging and successfully applied to real-world issues and problems. Based on the results achieved to date, it is concluded that FEM modeling is a cost-effective and worthwhile tool for forging product and process development. It has integrated design and manufacturing

allowing access to new markets, making new products, and using new materials. Customers can have custom-designed solutions in a fraction of the time it took using the "tried-and-true" methods.

Based on the initial successes described above, work will continue on 3D cogging applications and the range of forging-related issues that can be addressed using ANTARES will be expanded. The company has also planned to extend the use of 2D/3D FEM-based modeling to other areas, including ingot teeming. It is anticipated that all new processes and products will be modeled in some way on the computer prior to their implementation. ProCAST™ [23,24], a 2D/3D FEM package for modeling of casting, is also being evaluated to improve the casting process before forging so that the overall quality of the part is increased.

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