Forging Simulation Tool Based on Breakthrough Technology

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MSC.SuperForge is a new code developed for performing 3-D analysis of hot, warm and cold forging processes. Unlike traditional finite element based forging simulation codes, it employs a finite volume mesh for tracking material deformation and an automatically refined facet surface to accurately track the free surface of the deforming material. In this approach, the deforming workpiece material simply flows through a (fixed) finite volume mesh. To keep track of the free surface of the deforming material, the material flowing through the finite volume mesh is encapsulated by a geometric facet surface, which precisely tracks the exact material surface by automatically refining itself throughout the analysis. This new approach is both fast and accurate since flow calculations are performed on an undeformed finite volume mesh and robust since remeshing techniques are completely eliminated. This paper describes the development history and methodology of MSC.SuperForge, and outlines its advantages for simulating 3-D forging processes.

1 Introduction

The design of dies and the selection of process conditions in forging operations are today still performed to a large extent by trial-and-error methods. In many cases, this trial-and-error procedure is neither optimal nor cost effective in terms of achieving the desired properties in the finished product. With the development of numerical analysis techniques, the finite element method was introduced in the early 1980's as a viable alternative. The finite element (FE) method has been extensively researched by several research groups. The industry is using two-dimensional FE codes but has not as yet embraced three-dimensional FE codes (1). In this paper, the authors summarize the reasons for that, the lessons to be learned after 20 years of FE experience in forging simulation as well as a new breakthrough in forging simulation technology.

2 Three-Dimensional FE Simulation in Forging Industry

Three-dimensional (3-D) forging simulation based on the conventional FE technology is still not being readily implemented in the forging industry (1). Translation of 3-D simulation results into forging practice is for almost none percent successful while 2-D is between 85-90% successful (2). According to reference (2), 3-D simulation is still not a viable alternative for physical testing because of quality of results, turnaround time of project and lack of human resources.

2.1 Quality of Results

The prediction of metal flow, stress, strain and temperature distributions requires accurate and robust algorithms. Since the process of forging is typically characterized by gross 3-D material deformation and continuously changing boundary conditions, forging is a very complicated forming process! The participants of IDS (2) reported quite some mismatch between simulation results and experiments.

Besides this mismatch, the complexity of the forging simulation requires much simulator expertise and sometimes "tricks and tweaks" to produce a full solution (3). Tuning of numerical parameters is often required for a complete solution. For example, tuning of penalty coefficients for both contact and incompressibility conditions as well as adaptive remeshing is a common practice in 3-D FE calculations.

2.2 Turnaround Time

The participants of IDS (2) also reported too long turnaround times of 3-D simulation projects. Projects longer than 1 month was not very uncommon. Reasons for that can be seen in excessive CPU times, tedious conversion from CAD to simulation and cumbersome manual intervention.

In order to optimize tool designs, the user must be able to perform parameter studies that require relatively short calculation times. However, FE methods are relatively time-consuming to use. Even rather simple 3-D applications can take several days on a workstation. Simulation of an industrially relevant forging process was reported to take 19 days running in parallel on a 4-CPU machine (2).

Another reason for long turnaround times is the tedious conversion from CAD to simulation. Since requirements for a CAD geometry used in CNC path generation do not match those for use in a simulation code, a lot of "clean-up" work needs to be done in making the transition to a computational mesh before the actual simulation can be carried out.

Finally, too long turnaround times of 3-D simulation projects can be caused by manual intervention. Because of the complexity of the FE calculation, premature termination of the simulation is not unlikely. Either manual remeshing or restarting with new penalty coefficients are often required.

2.3 Human Resources

In practice, there is a gap between the language of the traditional tool designer, and the modeling code developer. One is thinking in terms of actual process characteristics and the other in terms of mechanical models. There remains a need of simulation code expressed in the terminology of the forge shop floor (4).

In addition, a high level of simulator experience is required to be able to "tune" the FE results. As mentioned previously, the "right" penalty coefficients for contact, incompressibility and remeshing needs to be chosen. This implies that a FE expert is needed but such a person is usually not available in the forging industry. In particular, the smaller size forging company cannot afford to have a FE expert in-house.

3 Technical Methodology

With the above challenges in mind, MSC started performing forging simulations with MSC.Dytran, a 3-D analysis code for analyzing highly nonlinear, short-duration events involving the interaction of fluids and structures, or problems involving the extreme deformation of structural materials. MSC.Dytran employs an explicit dynamics procedure in a finite element and finite volume method. It appeared that the finite volume method is well suited for 3-D forging simulations: MSC.Dytran was selected by Sumitomo Heavy Industries to participate in a Japanese National Forging project.

3.1 Finite Volume Method

The finite volume method is common practice for material flow simulations of events like sloshing, underwater explosion and helicopter ditching. Unlike a traditional FE mesh which distorts while attempting to follow the deformation of material, the mesh is a fixed frame of reference and material simply flows through the finite volume mesh. Forging typically involves large material flow as well.

Fig. 1 Sloshing and underwater-explosion simulations using finite volume method.

MSC.SuperForge was developed based on finite volume rather than finite element technology. This finite volume technology is particularly suited for simulating the gross material deformations inherent in forging operations, and at the same time completely eliminates the need for volume remeshing techniques, commonly considered the main bottleneck in 3-D forging simulations based on the finite element method.

For evolution of stress and impulse waves, an acoustic-advection solver has been developed. The face values of the finite volume elements can be solved from the Riemann problem (7) posed at the element faces. All nine state variables of the set of acoustic equations are evaluated in a Runge-Kutta (multi-stage) time integration scheme. The updated velocity field u is used in the advection solver. The advection equations are solved with 2nd order upwind scheme using MUSCL (8).

Monotonicity is preserved by the nonlinear limiting function Superbee. A more comprehensive description of the technology can be found in (5) and (6).

3.2 Automatic Surface Tracking

Since a finite volume solver simply tracks the material volume fraction (FMAT) per finite volume element, the orientation and exact position of the free surface are not adequately defined. In addition, FMAT methods tend to be diffusive and do not preserve material shape accurately. From studies performed at the Univ. of Michigan (8) and the Center for Mathematics and Computer Science (9) in Amsterdam, MSC concluded that the free surface should be explicitly defined in the finite volume method. In this way, the advantages of the finite element and the finite volume approach could be combined: natural representation of the free surface and that of gross 3-D material deformation, respectively.

The shape of the workpiece is obviously of paramount importance in any forging operation. A new concept of a facet surface is therefore developed to accurately track the surface of the workpiece material throughout the simulation. With this technique, the material flowing through the finite volume mesh is automatically encapsulated by a geometric surface comprised of triangular facets. These facets are not finite elements, but rather geometric entities which collectively serve as a convenient mechanism for tracking the exact material surface. The facet surface is constrained to move with the material which it encapsulates and thereby also allows the precise application of boundary conditions to the material, either from contacting dies or from the free surface of the material itself.

3.3 Resolution Enhancement Technology

Resolution Enhancement Technology (RET) has also been developed to automatically refine the facet surface throughout the simulation. RET is useful because in most cases, continuous refinement of the facet surface is necessary to ensure that it accurately captures the continuously changing and increasingly complex geometric details of the workpiece material. One of the main tasks of RET is to refine the material facet surface at locations of the die(s) which have significant curvature. The facet surface must be capable of "folding" around the features of the die surface. The technique of RET will be published in a separate paper.

In sharp contrast to remeshing algorithms in finite element based forging simulations, RET poses no numerical problems or instabilities in the solution. There are no constraints on the degree of refinement of the facet surface since the facets are geometric entities rather than finite elements. Therefore, common problems associated with finite element based remeshing algorithms, such as degradation of the solution due to severe element distortion and excessive CPU processing times, are avoided with MSC.SuperForge.

3.4 Kinematic Contact Algorithm

Interaction between rigid dies and the deformable workpiece material is modeled with contact surfaces, in which contact conditions are kinematically enforced between the die surfaces and the facet surface of the material. The explicit contact algorithm achieves exact satisfaction of the contact conditions in a non-iterative way. Each material surface point is followed within each time step. The non-iterative nature of the contact algorithm makes it very unlikely that the analysis will fail due to difficulties with contact. In addition, it completely avoids penetrations common to penalty-based contact algorithms. Penetrations are, of course, unacceptable because its accumulation in time might yield significant loss of material.

It is important to note that in the kinematically enforced contact algorithm convergence is always guaranteed. This represents a significant advantage over the penalty-based contact algorithms that try to choose the "right" penalty coefficients. Especially in strongly nonlinear problems many iterations are often necessary with either changed penalty coefficients or increased convergence tolerances. Within an engineering environment, this is very costly, time consuming and error prone.

3.5 Forging Specific GUI

In the past, it was necessary to spend days developing an accurate 3-D model. Use of a modern Graphical User Interface (GUI) enables a significant reduction in elapsed time required to develop a model. Data transfer between external CAD systems like Unigraphics, ProEngineer, CATIA, CADDS5, and any simulation system should be fast and without loss of geometric information. Due to recent developments in GUI of codes such as MSC.SuperForge, fast and efficient transfer becomes possible.

In addition, current developments in GUI are towards bridging the gap between the language of traditional forger, and the code developer by using forging terminology from the forge shop. For example, the motion of a crank press can be represented by simply defining the actual press characteristics (i.e., stroke, revolution speed and rod length). Besides press characteristics, material properties can be stored in a database such that reuse of these data is easily possible.

Finally, developments in GUI are focussed on ease-of-use. An advanced technique like RET enables new developments towards "meshless" forging simulations: since the finite volume mesh and the (initial) material surface mesh are very simple, it can be automatically generated and hidden from the user. In this way, simulation tools become better accessible to traditional forgers.

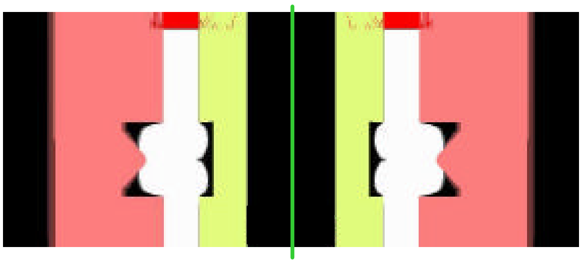
4 Industrial Examples

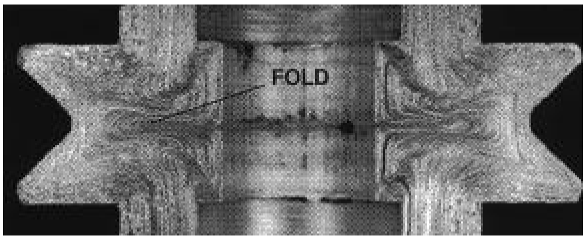
In the following sections, three different examples are reviewed to demonstrate the feasibility of 3D forging simulations with MSC.SuperForge. The calculations were carried out on a workstation with a SPECfp_rate95 of 90.

4.1 Radial Extrusion of a Pulley Component

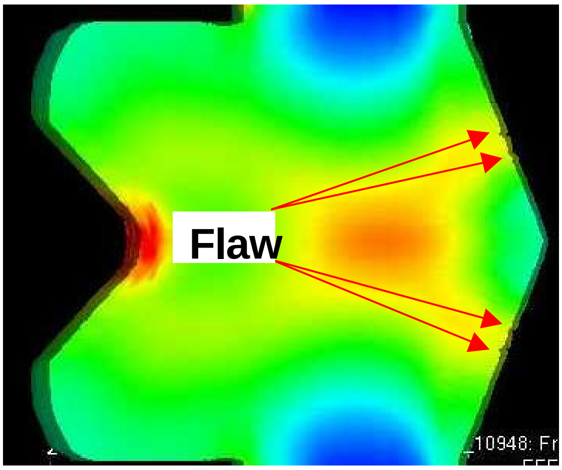
In this example, a pulley part is forged by extrusion from a pure aluminum tube (3). Its flange to wall thickness ratio is approximately 2.0. The design question rises whether you can produce this part with or without preforming.

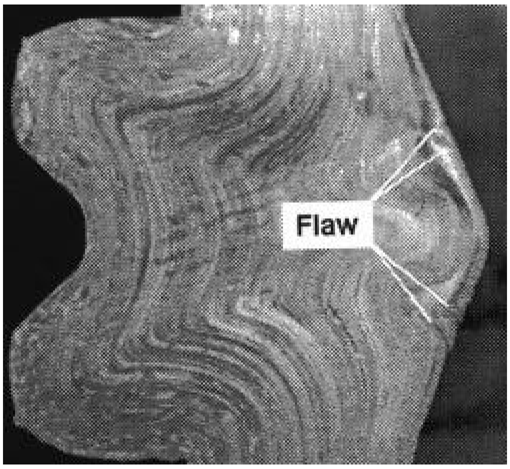
From the simulation, it is clear that folding already starts at 40% of height reduction (Fig. 2). Figure 3 is showing the experimental fold.





With the preforming stage, the fold could be avoided. However, some flaws on the surface of the workpiece could clearly be detected.





4.2 Hot Forging of Dual Connecting Rods

In this example, dual connecting rods are forged from a single piece of stock. The forging process consists of a buster, blocking, and finishing stage. Relevant material properties such as effective plastic strain and temperature are automatically transferred from one stage to the next stage in the simulation. Starting with a round bar stock, the buster operation is used to widen and flatten the forging stock. Part of the material is being squeezed into the flash region, and the outline of the connecting rods is already visible in the blocking stage (**Figure 6**). The blocking stage simulation took 12 CPU hours.

Figure 7 shows the final shape of the connecting rods after the finishing operation. Geometric details can clearly be observed along with sharp corners at the heads of the connecting rods. As compared to the experiments performed at Sumitomo Heavy Industries on a crank press, the flash region and the extent of die filling are in good agreement.

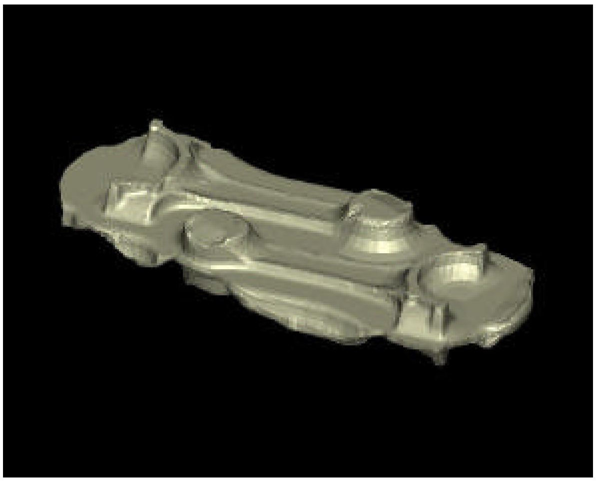


***Figure 6** - The final shape during the blocking operation of dual connecting rods.*

***Figure 7** - Final shape of dual connecting rods at the end of the finishing stage.*

4.3 Hot Forging of a Crankshaft

In this example a crankshaft from Nissan Motor Company is forged. An intermediate stage in a multi-stage forging process is shown. The 30 kg crankshaft is forged from a rectangular steel block 92 mm square by 520 mm long (**Figure 8**).

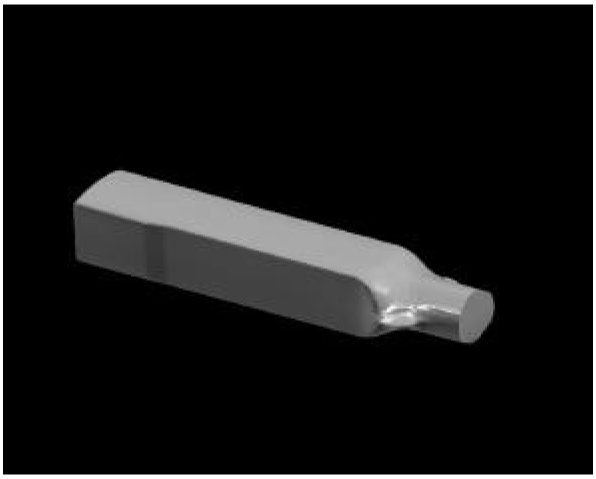


Figure 8 *- Preform used in forging operation of the crankshaft.*

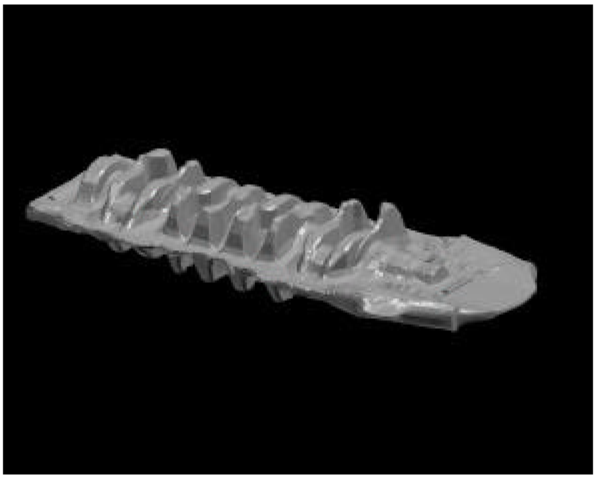


Figure 9 *- Final shape of the crankshaft in intermediate forging operation.*

The actual forging process was performed on a hydraulic press, and therefore a constant speed is imposed on the upper die. **Figure 9** shows the final shape of the crankshaft. The simulation took 12 CPU hours.

5 Conclusions

This paper presents a new method for performing 3-D forging simulations. In this method, the advantages of the finite element and the finite volume approach are combined: it employs a finite volume mesh for tracking material deformation and an automatically refined facet surface to accurately track the free surface of the deforming material. This new approach included in MSC.SuperForge, is both fast and accurate since flow calculations are performed on an undeformed finite volume mesh and robust since remeshing techniques are completely eliminated. The robustness and relative efficiency make it an ideal tool for 3-D forging simulations in which high resolution of material flow details is desired with reasonable CPU processing times.

6 References

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