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SIMULATION BASED PROCESS DESIGN FOR IMPROVEMENT OF PROFITABILITY IN THE HOT FORGING INDUSTRY

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ABSTRACT

Global competition has intensified in the manufacturing world in general, and specifically in the forging industry. Forging firms from developing countries, have the advantage of an inexpensive and highly motivated labor force. Some of these countries also receive support from their government in the form of tax breaks, free training, and an artificially maintained favorable foreign exchange rate. Thus, the forging industry of industrialized high labor rate countries can only survive in this global market by reducing labor costs, increasing material utilization by reducing flash and scrap losses, by reducing lead times and above all by maintaining a technological advantage over their competition.

1 INTRODUCTION

Global competition in the forging industry has brought to the forefront the issues of managing innovation and technological development while demanding continuous improvement of products and processes. To reduce labor costs, the buyers of forgings tend to seek new suppliers from developing nations for purchasing components with high labor content. In order to succeed in the global marketplace, forging suppliers from developed nations must focus on production of high value-added forgings, finished parts and sub-assemblies with the aid of new developments such as a) advances in the use of computer modeling in forging process development, b) advances in equipment design, c) use of innovative tool design for complex forging operations, d) appropriate training in advanced forging technologies, and e) information management and automation in forge shops.

2 IMPROVEMENT OF PROFITABILITY IN FORGING

The profitability of a forging process depends upon various factors such as a) material utilization, b) defects and scrap rate, c) die wear and tool service life, d) utilization of forging equipment, e) selection of (optimum) process parameters by use of engineering tools such as FE simulation, f) automation and labor content, and g) information management to name a few. Thus, to survive and make reasonable profit in today's highly competitive environment, leading forging companies must:

a) increase material yield/utilization by 1) maintaining quality/reducing scrap rates and 2) reducing flash losses. This issue is becoming increasingly important since material costs continue to increase because of higher than usual demand from Asia.

b) reduce die wear and increase die life.

c) introduce advanced die making methods to reduce lead time in die manufacturing and reduce die costs.

d) implement process modeling techniques using 3D Finite Element (FE) based simulation software. Thus, preform, blocker and finisher dies are designed properly and within relatively short time, instead of using trial and error methods that require highly skilled manpower and long lead times.

e) work with their customer in developing "forging-friendly" assemblies and components for future applications.

The implementation of these action items, require a conscious effort towards improving the technical expertise of forging companies by making appropriate investments in hardware, software and human resources.

3 SIGNIFICANCE OF COMPUTER AIDED ENGINEERING (CAE) IN FORGING

Nearly all forging companies use computer aided design (CAD), computer aided manufacturing (CAM) and Engineering (CAE) for die and part design and die manufacturing. Finite Element (FE) based process simulation is also used by a large segment of the forging industry to analyze and optimize the metal flow and conduct die stress analysis before conducting forging trials (1). Thus, part development time and cost are reduced while quality and productivity are increased. For instance, in 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. Figure 1 illustrates the role of FEM in forging process design by means of a block diagram (2).

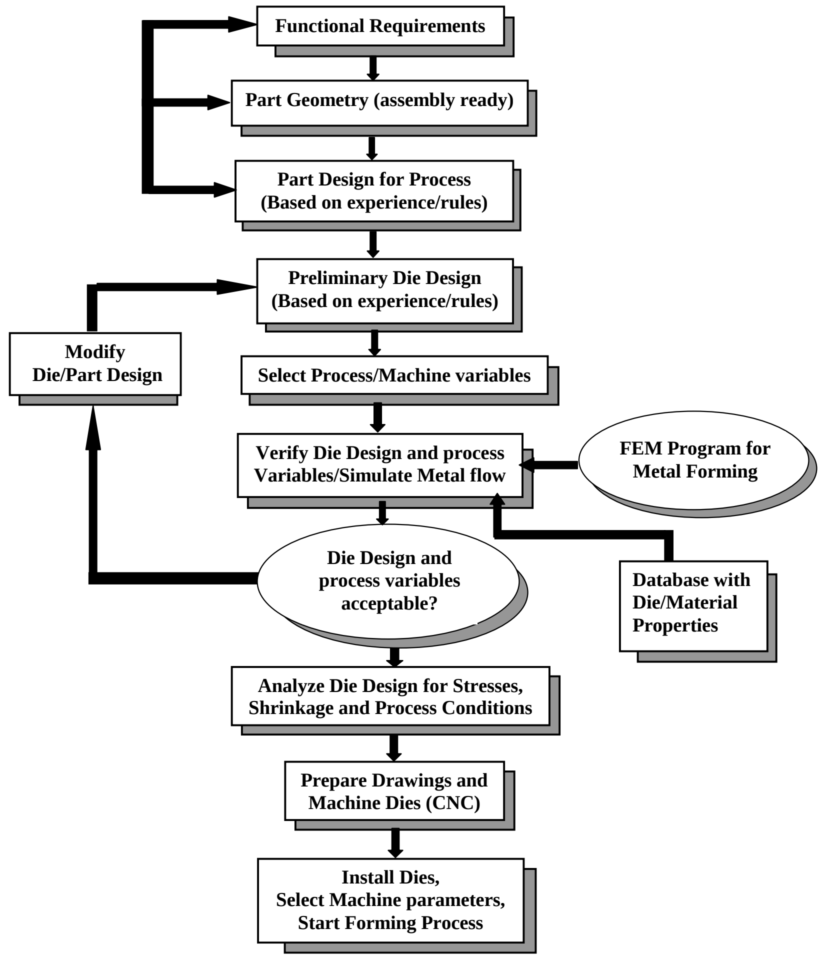


Figure 1: A flow chart illustrating forging process design (2).

3.1 Determination of Reliable Input Parameters for Process Modeling

The accuracy of FE process simulation depends on reliable input data namely, a) CAD data of the die geometry, b) speed and force/energy characteristics of the press or hammer used for forging, c) flow stress of the deforming material as a function of strain, strain rate and temperature in the range relevant to the process being analyzed, and d) friction characteristics at the interface between the deforming material and the die. The tool geometry and forging equipment characteristics are known. Material properties of the deforming material and the friction conditions need to be estimated through tests that emulate production conditions. (2 to 5)

3.2 Improvement of Material Utilization in Hot Forging

3.2.1 Material Yield Improvement in Hot Forging of an Automotive Component from Aluminum Alloy

In hot forging with flash a considerable amount of input material may be lost into flash. Material costs constitute a major chunk of the finished part cost besides labor, thus presenting the opportunity of huge cost savings if volume losses in flash can be reduced. Also, customers often demand very quick response to Request for Proposals (RFP's) & rapid part delivery after placing an order, thus necessitating the use of an efficient design and quotation process. In order to maximize the material savings it is necessary to:

- Identify the optimum shape and size of the preform with the best possible material distribution to obtain complete cavity filling without defects.
- Modify the flash design of blocker & finisher die to minimize the loss of material into flash.

The ERC/NSM has conducted studies for a sponsor to optimize the preform and die (blocker and finisher) designs, forging temperatures as well as flash dimensions. Due to confidentiality, Figure 2 shows an example part similar in geometry and processing sequence to the one being evaluated in one of our studies. The automated forging sequence consisted of the following operations:

- induction heating of forging stock,
- two stage hot rolling of incoming forging stock for material volume distribution,
- hot bending,
- blocker forging,
- finisher forging and
- trimming.

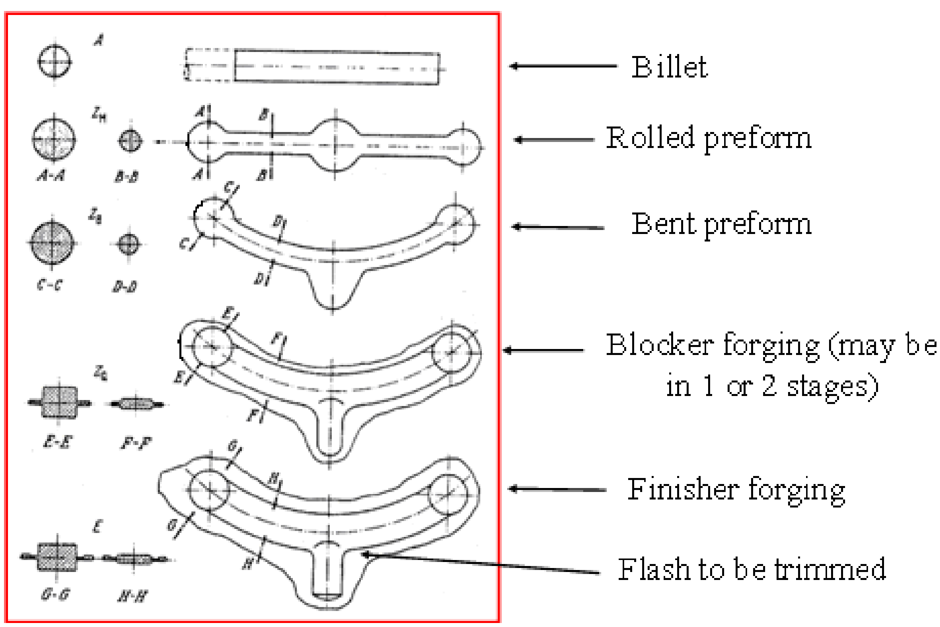


Figure 2: Illustration of the hot forging sequence for upper control arms using an example part (5).

In the example under consideration, initial material yield was ≈ 71 % (Final part volume: 131 in^3; Initial billet volume: 183.22 in^3). The following strategy was employed for improving the material yield:

Step 1: 3D simulation of current billet preforming (reducer rolling) and forging operations to validate the FE simulation model of the forging process (Figure 3).

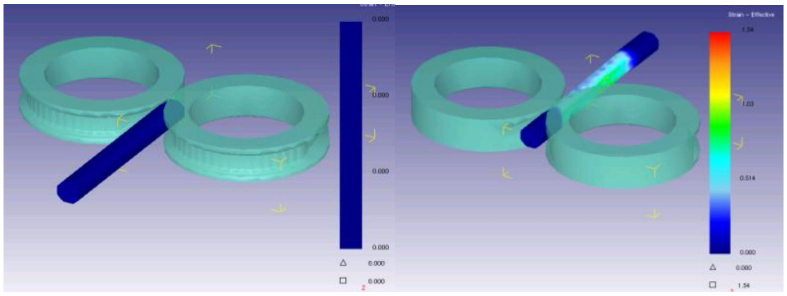


Figure 3: Simulation of the reducer rolling process.

Step 2: 2D simulations at various sections/locations on the preform using the assumptions of plane strain/axisymmetric flow to optimize the shape & size of the preform and the design of the blocker die

Step 3: 3D simulation of sections which cannot be analyzed in 2D FEM using simplifying assumptions (Figure 4).

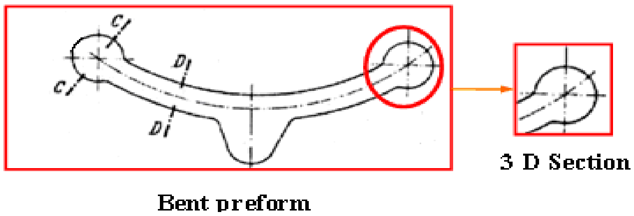


Figure 4: FE simulation of 3D sections.

Step 4: Final validation of the optimized preform shape and blocker design using 3 D simulation of the forging process (Figure 5).

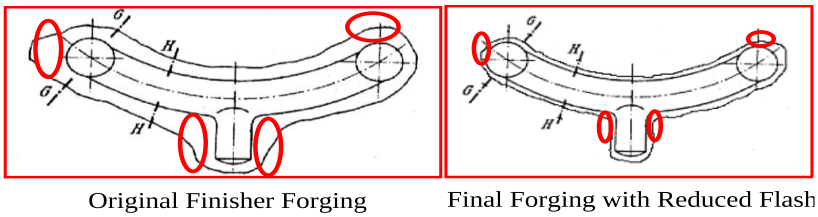


Figure 5: Final validation with 3D FE analysis.

Step 6: Forging trials with new preform geometry and blocker die design

Based upon FE simulation results the material yield was increased from 71 % to 86 % with only preform optimization i.e. the incoming forging stock and reducer rolling operation were optimized to improve the material yield with the existing dies. A potential improvement of a further 3-4% is expected upon completion of the blocker design study. Thus, an FE simulation based design study is expected to improve the material yield by $\approx$ 19% in hot forging of a high volume automotive component.

3.2.2 Material Yield Improvement in Hot Forging of Front Axle Beams

A similar study was conducted at the Royal Institute of Technology - Sweden with funding from Imatra Kilsta AB. Figure 6 shows the closed-die forging of a front axle beam meant for heavy trucks (6). The amount of flash obtained in production constituted 35% of the total workpiece weight, which was equal to 115.4 kg. The strategy for improving the material yield was to modify the initial forging workpiece geometry, keeping the blocker and finisher die geometries unchanged. This was done by recommending new shapes for certain cross-sections of the reducer-rolled billet. The goal was reached by using a quasi-3D analysis i.e. by using 2D FE analysis using a plane strain metal flow assumption. Three critical cross-sections that showed close to plane strain conditions during forging were chosen for the analysis. The loss of material in the sections caused by axial material flow were measured from full-scale experiments (Figure 8) and added to the optimized cross-sectional areas established from the FE-analysis. Based on recommendations from the customer the initial cross-sections used in the 2D-forging simulations were chosen to be circular. Using FE simulation, the theoretical material yield was increased by 2.58–7.59% for the cross-sections. Results from this work have facilitated the redesign of the reducer rolls to reduce the flash volume generated in production.

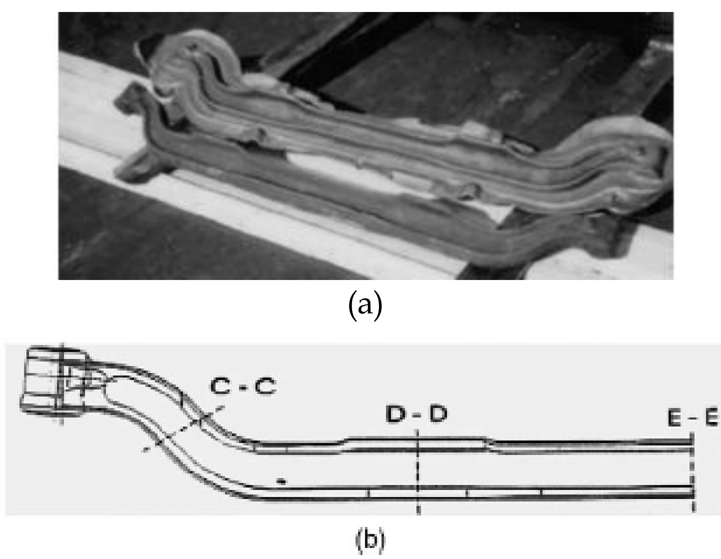


Figure 6: (a) The front axle beam after finishing forging including flash. (b) Positions of the cross-sections analyzed (6).

3.2.3 Material Yield Improvement in Hot Forging of Steering Knuckles

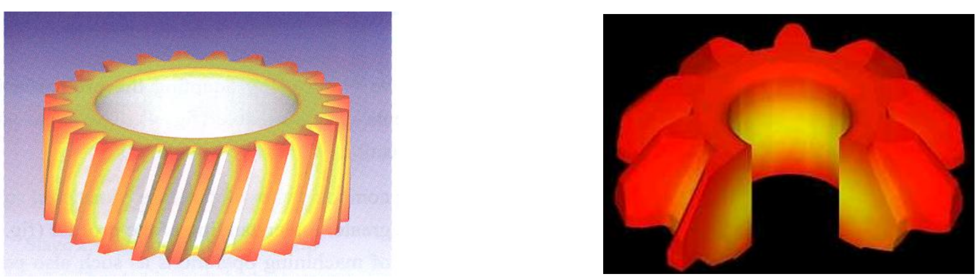
The material tracking function available in commercial codes such as DEFORM® or FORGE3® for tracking grain/metal flow can be used to identify material optimization areas without an extensive FE simulation study. Such a study was done by CDP-Bharat Forge Gmbh using FORGE3® (7). The area of surplus material was marked after the blocker simulation. Backward tracking was then used to identify the material location on the initial preform.

The material utilization ratio on most forged steering knuckles is in the range of 60-70 % depending upon complexity and configuration. The initial process for forging the horizontal knuckle forging consisted of simple upsetting, blocker and finisher operations with a yield of 70 %. The material flow was limited to the upsetting and blocker processes. Based on an FE analysis study, two more forging operations were added to distribute the material in desired areas. The expected weight saving was 5 kg with a 12 % increase in the material yield.

3.3 Process Design, Analysis and Optimization

3.3.1 Simulation of Heat Treatment

Heat treatment after forming is of great interest to the metal forming process designer since it determines the final mechanical properties of the part as well as dimensional stability after processes such as quenching. It is also possible to optimize the heat treatment as desired, change carbonization depth or prevent hardening distortion (Figure 7 a). In Figure 7 b dark regions show the volume fraction of martensite transformation and light regions indicate a mixture of bainite and pearlite.



(a) **(b)**

Figure 7: Heat treatment simulations of gears (11).

3.3.2 Incremental Forming Methods

Simulation of incremental forging processes requires extensive computer time because a very small time step size must be used because of localized deformation, in addition to the increased cycle time needed to yield the desired geometry. Thread rolling, orbital forming, ring rolling etc are examples of such processes. For example, thread rolling simulation with so-called “rigid zones” can be accomplished within a few hours (8) on an efficient laptop.

At the ERC/NSM, orbital forging simulations using DEFORM-3D® were conducted to study and develop a robust assembly process of an automotive spindle and an outer ring. Figure 8 shows the simulation progression, which considers elastic and plastic deformation, residual stresses, and quality of assembly. This application illustrates the current capabilities of FEM using the commercial software DEFORM-3D® in simulating complex and incremental cold forging operations to optimize process conditions and product design (9).

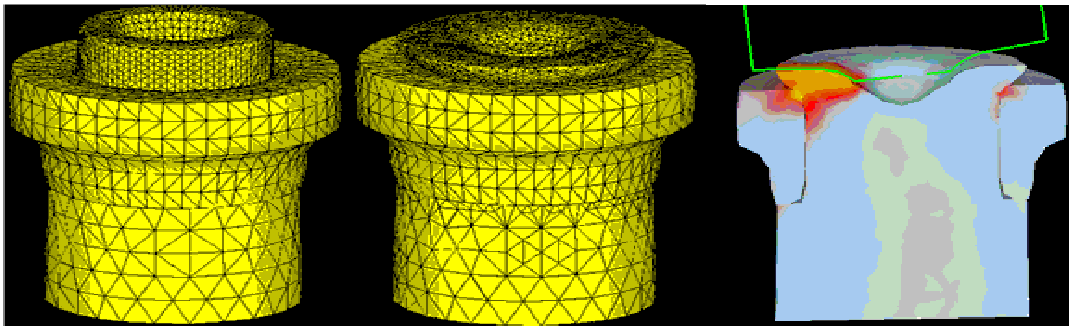


Figure 8: FE simulation of orbital forming (FE model and stress distribution) (9).

Ring rolling is used in production of large annular components in aircraft engines. It is also a common process for producing gear and bearing components for automotive and other applications. It is now possible to model, within reasonable computing time, the non-isothermal ring rolling processes with axial rolls to determine the ideal perform design for obtaining complex cross sections, as seen in Figure 9. Typical processes involve dozens of revolutions of the workpiece, with localized deformation. While the workpiece appears axisymmetric, this is a three-dimensional process. Historically, process models have been computationally intensive (slow) or over constrained, resulting in questionable accuracy. New simulation techniques are available to practically simulate the ring rolling process.

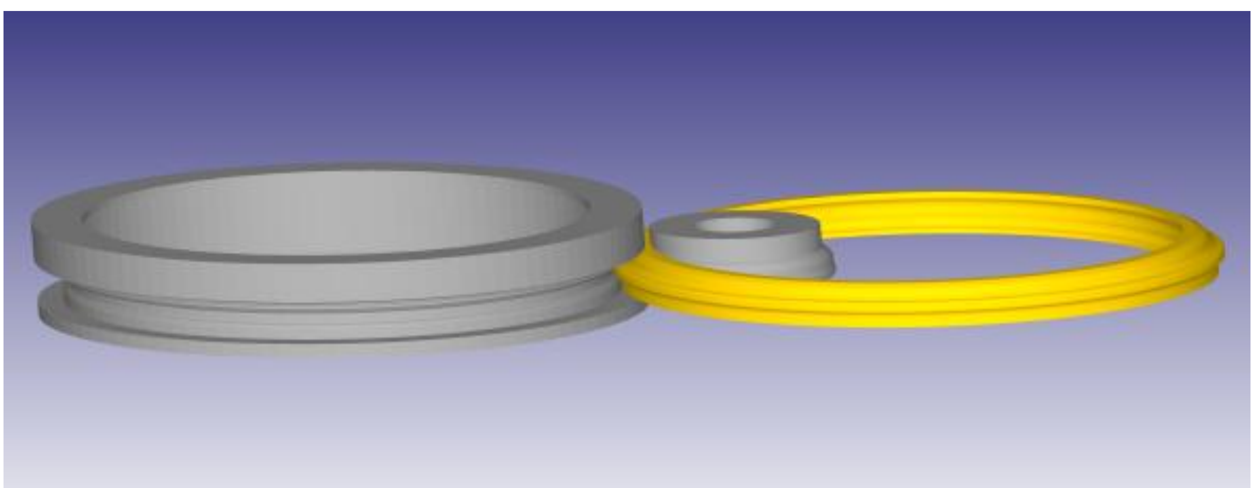


Figure 9: An aerospace component is shown at the end of a ring rolling process

3.3.3 Die Life Improvement in Cold/Warm/Hot Forging

Estimation of die wear is extremely crucial to forging process design since die costs (manufacture and maintenance) account for a significant portion of the final part cost, quality and process efficiency. Today, it is possible to estimate die wear for a given die material and hardness. The FEM simulation predicts temperatures, pressures and sliding velocities at the die-forging interface. This information together with the knowledge of the variation of die surface hardness (as a function of temperature and time) provides estimated die wear using the well known "Archard" model [5].

3.3.4 Prediction and Optimization of Forging Microstructure

By utilizing the traditional Johnson-Mehl-Avrami-Kolmogorov (JMAK) approach to model recrystallization kinetics and grain size evolution, it is possible to model grain size evolution in forging and heat treating aerospace alloys. The microstructure of a material provides information linking its composition and processing to its properties and performance, thus modeling is paramount to optimum process and product design.

The DEFORM Microstructure Module was used to predict the final grain size of a multi-step hot die forging of a waspalloy jet engine disk. During the forging process at Carmel Forge, the grain growth and recrystallization kinetics were modeled. The predicted results matched very well with the actual grain size distribution observed in the cut up section of the waspalloy disk as shown in Figure 10 [12].

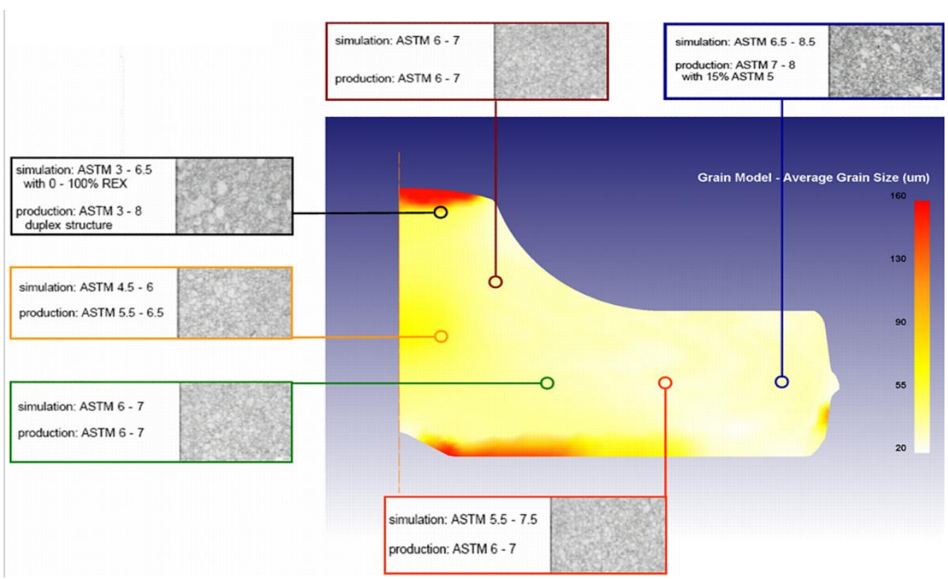


Figure 10: The correlation between the simulation and production grain size [12]

3.3.5 Design Verification using FE Analysis

Figure 11 shows, as an example, multi-stage forging simulations of an aircraft aluminum wheel to predict metal flow, temperature distribution, die filling and die stresses (5). Flash removal between the forging stages also had to be considered for the simulations in order to ensure appropriate material volume in the dies for the subsequent forging stage.

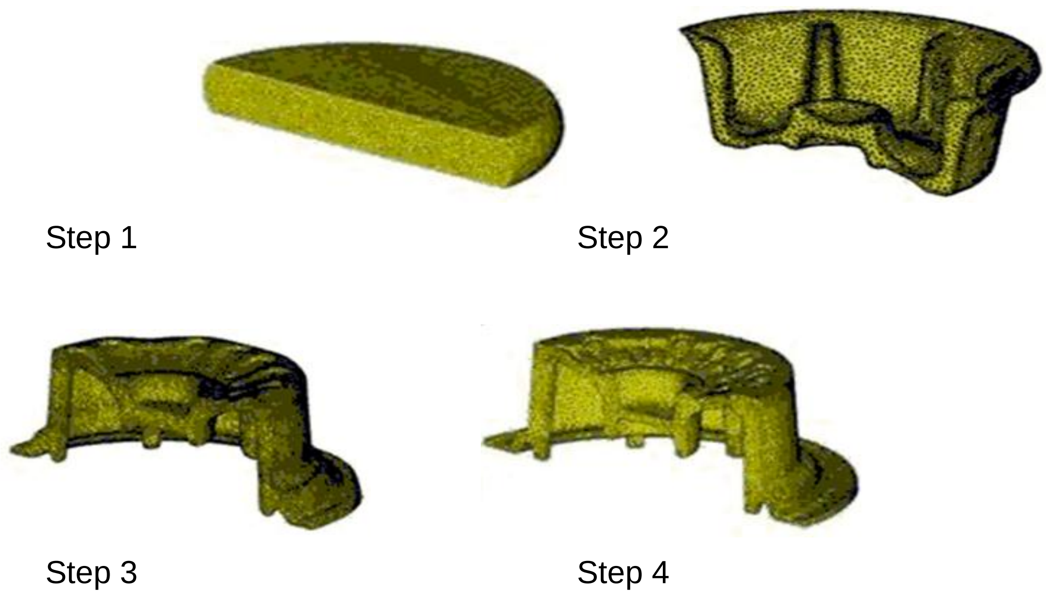


Figure 11: Forging sequence of the aircraft wheel (part geometry courtesy of Weber Metals Inc.) (5).

4 SUMMARY AND FUTURE OUTLOOK

Competition to the forging industry comes from two primary areas: competing processes and materials and the highly competitive global industry. In order for the forging industry to remain viable and successful, there is a need for a comprehensive approach, through alliances, to support and address the research and development programs for reducing costs and lead times and increasing material utilization (29). Global off-shore forging competitors are further strengthened by trade offset programs, direct and aggressive foreign government support, lower labor costs, and relatively cheap cost of capital.

The forging industry faces the following challenges which should be taken into account for project selection and identification of technology improvement opportunities:

- There is a growing need for engineering graduates with exposure or competency in computational engineering aids and know-how about the practical aspects of precision forging and manufacturing.
- Experience and knowledge-based product and process design software tools with user-friendly interfaces as needed to help the designer/process engineer in forging sequence and die design selection.
- Generating a more complete material database for important engineering alloys, die materials and lubricants are essential to support process design, including better data for both material and interface heat transfer for heat treatment and quench path modeling.
- Design rules are necessary for designing surface heat transfer coefficients for 3D objects and a geometrically robust 3D inverse analysis method for analyzing experimental results as a function of geometry (shape features and surface inclination angles), quenching medium, bath temperature, part temperature and time.
- It is useful to develop and maintain a database of equipment types and characteristics to control aspects of the forging process such as part tolerance, die deflection, heat transfer between tool and workpiece, etc. to accurately simulate forging processes.
- Guidelines for prediction of the final microstructure and mechanical properties of forged components, both hot and cold, should be developed.

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