ROLE OF COMPUTER SIMULATION IN DEVELOPMENT OF CLOSED DIE HOT FORGING PROCESS –A REVIEW

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Abstract- In recent years, metal forming industry utilizes practical and proven CAD, CAM and CAE techniques. The development of numerical simulation methods has created new feasibilities with great industrial aspects as regards optimization of metal forming processes. Using analysis techniques, it is now possible to predict material properties, material flow, strains, temperature distribution, die filling, defect creation (if any), die stresses (for preventing premature die failure), optimizing process variables, visualizing internal material transformation and product characteristics. This paper summarizes the modern techniques and future trends of simulation technology and reviews various applications in most important forming process i.e. closed die hot forging to meet the heavy demands to manufacturing industry for faster, better and cheaper production.
Keywords: Hot Forging, Simulation, FEA/FEM, Optimization.

1. INTRODUCTION

Forging is a widely used manufacturing process for the mass production of complex, high-precision parts. A forging process resulting in the minimum possible number of operations and minimum production of scrap is the desirable due to cost factor as compared to other processes. Finite element analysis (FEA) of the forging process is a proven computational method which enables the tool geometry, material and friction conditions to be accurately modelled. The different characteristic behaviors of materials may be input to the finite element simulation tool to enable the process and tool design to be optimized. In metal forming, the Finite Element (FE) based process simulation is used to predict metal flow, strain, temperature distribution, stresses, tool forces and potential sources of defects and failures before conducting trials. In some cases, it is even possible to predict product microstructure and properties as well as elastic recovery and residual stresses.

In forging, simulation of 2D problems, e.g. axisymmetric and plane or near-plane strain, is truly state of the art. Despite long computation time; the applications for 3D problems are also widely used in industry using advanced simulation techniques now a day.

The main reasons for use of process simulation include reduced time to market, reduced tool development cost, prediction of process parameter's influence, better understanding of material behavior and reduced material wastage and always better product quality.

Major goals achieved during hot working process using process simulation techniques include accurately prediction of material flow, determination of die filling, prediction of laps/defects if present, determination of stresses, temperatures, and residual stresses in the work piece; also using simulation techniques advance properties such as grain size, local hardness, phase change and composition and material damage is possible to determined.

The most important step during product and process for metal forging is design of product as well as tool geometry. It is well known that the design activity represents only a small portion, 5 to 15 %, of the total production costs of a part. However, decisions made at the design stage determine the overall manufacturing, maintenance and support costs associated with the specific product [1]. For particular forming process-the specific factors, generated by simulation provides efficient manufacture of products of specified properties with greater response.

2. SIMULATION TECHNIQUES AND PROCEDURE FOR METAL FORMING PROCESSES

It is already briefly mentioned, the requirement of higher efficiency, that only offered by process simulation, has great significance in metal forging application as compared with other manufacturing techniques. The extensive cost of tool/die production and the towering cost of the forging machines force the increasing use of modern, efficient methods and procedures of process simulation.

The historic expansion of the numerical and analytical i.e. mathematical methods and techniques of simulating forming operations can be divided into two periods as described in Fig.1. In the period prior to efficient use of the computer (prior to approximately 1960) mostly empirical simulation procedures were in use. Through the organized experimental study of

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parameters (partly involving the use of similitude mechanics) fundamentals were produced for determining forming forces, material flow and failure phenomena.

The theoretical simulation methods (analytical) were based mainly on elementary plasticity theory and sought to compute the forming forces and roughly estimate the stresses. For example (i) Uniform Deformation Energy Method (ii) Slab Method (iii) Slip line Field Method (iv) Visio-plasticity Method (v) Upper Bound Method were the earlier used methods, limit their capabilities for handling complex metal forming cases such as closed die hot forging process. A detailed description of the elementary plasticity theory is contained, for example, in [2]. To a smaller extent, methods based on slip line theory and upper bound methods were applied [3].
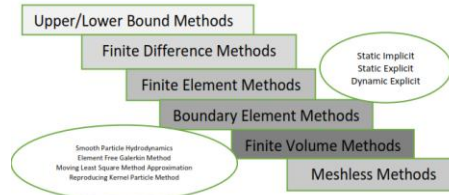

Fig.1. Different simulation techniques

The decisive aspect of the theoretical procedures was that they involved simple, closed analytical calculation rules, or that these theories were applicable by graphic methods (slip line theory). In view of the complexity of the mechanics of the deformation zone, the theoretical simulation techniques consequently entailed rough assumptions and simplifications, which, in turn, strongly impaired the meaningfulness of the data established with them. For this reason, around 1950 the first experiments were undertaken to simulate the forming process proper with the modelling materials [4].

With the availability of the computer, a real revolution in the field of theoretical simulation of forming processes began. High plasticity theory was applied due to popularity then. They were reformulated so that they can be used with numerical techniques which in turn were easy for computers to process. The development began with finite difference methods, went further with the consummation of error method, finally advancing around the year 1970 to the application of the finite element method. But it should be emphasized that the last mentioned techniques are only "numerical tools" for applying the plasticity theories. Thanks to these numerical tools it is now possible to determine in advance the flow of materials, the stresses, shape and failure phenomena, making full use of the foundations of plasticity theory.

Various major factors to be considered for selection of cost effective and reliable numerical simulation process include: Geometry representation, Meshing and Re-meshing capabilities, Characteristics of the simulation code (reliability and computation time), Workpiece and Tool Material Properties handling capabilities, and Interface conditions (friction and heat transfer) handling capabilities. Based upon these capabilities several commercial simulation codes are available, some of these are presented in Table 1.

Table 1. Commercially Available FE Programs for Forming Process Simulation

Name	Manufacturer, Country	Type	Application
ABAQUS	HKS, USA	Implicit	generally non-linear
MARC	MARC, USA/NL. D	Implicit	generally non-linear
NIKE3D	LSTC, USA	Implicit	generally non-linear
LARSTRAN	LASSO, D	Implicit	generally non-linear
INDEED	INPRO, D	Implicit	sheet metal forming
DYNA3D	LSTC, USA/	explicit, dynamic	crash, bulk, sheet metal
ABAQUS-explicit	HKS, USA	explicit, dynamic	crash, bulk, sheet metal
AUTOFORM	AUTOFORM, CH	Spec. formulation implicit	sheet metal forming
STAMPACK	QUANTECH ATZ, SA	Spec.formulation implicit	sheet metal forming
Autoforge	MARC, USA/NL, D	elastic-viscoplastic	bulk, forging
FORGE2/3D	CEMEF, F	rigid-viscoplastic	Forging
QForm	Quantor-Form Ltd. ,Forge Technology, Inc., USA	rigid-viscoplastic	metal forming
Simufact Forming	Simufact Engineering Gmbh (Germany)	rigid-viscoplastic	metal forming

Forge NXT	Transvalor, France		Metal Forming
DEFORM	SFTC, Columbus, ohio		Metal Forming,
OPENFORM	GNS - Gesellschaft für Numerische Simulation mbH		Sheet Metal Forming

Here, it can be generally emphasised that the accurate and efficient use of metal forming simulations requires not only a reliable FE solver but also:

1. Software packages for interactive pre-processing to provide the user with control over the initial geometry, mesh generation and the input data, automated re-meshing, and interactive post-processing that provide more advanced data analysis such as point tracking and the metal flow line calculation.
2. Analysis capabilities those are able to perform the process simulation with rigid dies, to reduce calculation time, and use contact stresses and temperature distribution from the process simulation with rigid dies to perform elastic plastic stress analysis.

The time required, to run simulation varies depending on the computer being used and the amount of memory as well as the work load such a computer has.

3. APPLICATIONS OF COMPUTER SIMULATIONS IN FORGING PROCESS

Computer simulation for forging process is a computer program is used to predict metal flow, die fill, load required, energy required. The metal flows to the path of lowest resistance when displaced by one or more dies. The press/hammer load depends upon forging size, shape, friction, and temperature and material properties. Simulation can directly determine stress, strain and temperature. Pre-determination of grain flow, shear bending and fracture may be predicted. For forging simulation it is necessary to have data on flow stress, i.e. true stress/true strain, in function of temperatures and strain rates that exist in the actual process. List of dependent process variables during closed die hot forging process is described in figure 2. Numbers of researchers have contributed forging process simulation using Finite Elements analysis (FEA) in both 2D and 3D versions.
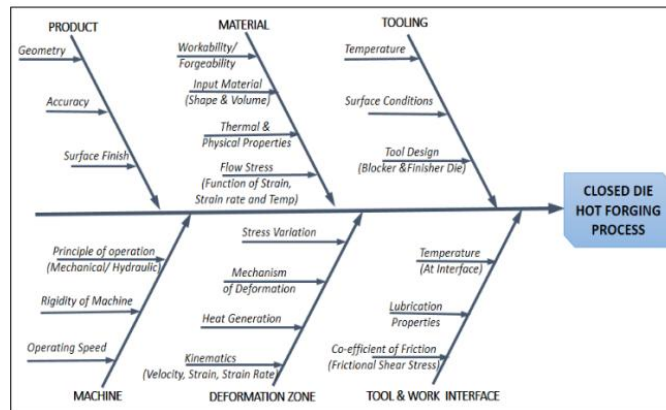

Figure 2: List of Process Parameters In Closed Die Hot Forging Process

A lot of published research work is available by various authors in form of conference journals, magazine articles and marketing brochures printed by simulation suppliers. Under forging process, various problems have been undertaken and successfully solved, are listed as below:

3.1 Die and Process Sequence Design in Forging

At early stages of the design process, knowledge-based approach have been used, however during the final and detailed design of the tooling stages, it is necessary to predict the behavior of forging tool/die, the stresses acting on the tools/dies, and the metal flow to assure that no flow induced defects at any of the forging stages. Process modelling is used routinely for this purpose by the industry. It is possible to calculate process variables and their effects, i.e., strains, temperatures and strain rates influence the microstructure development and properties of the formed part using the results of process simulation using repeated experimentation. Examples of such applications are available for forging micro-alloyed steels and hot forging of connecting rods [5].

3.2 Estimation of Die Failure in Hot Forging Process

Firstly wear model developed by Archard (1953) onto forging die wear remains the thrust research topic. [6] considered abrasive and adhesive die wear during the hot forging process considering hot hardness of materials. [7] explored a modified wear model to denote the room temperature hardness of the die in function of temperature and operating time, tempering parameter, considering thermal softening of die in elevated temperature forging processes. [8] suggested an advanced model in order to predict the effect of sliding velocity on wear in relation to the influence of the contact normal pressure between

workpiece and tool. Kim et.al suggested calculation of service life of hot forging dies; determined by plastic deformation, by applying a function of the tempering parameter [9]. Conor McCormack and John Monagham processed an entire forging sequence of a complex component of spline shape using Deform simulation software [10]. Forging defects and distortions during the process were analyzed and die areas most prone to fail were identified. Nikolai Biba et al. showed the advantages of using FEM to analyze forging processes [11]. Using Deform 3D, Young-Sang Na et.al have predicted the micro structural evolution in blade forging [12].

Life of brittle (ceramic) forging tools and dies prone to fracture and rupture has been determined in the POLLUX finite-element code, developed by INSA (Lyon) especially to simulate forging operations was applied by [13].

Stress and fatigue analysis by predicting the pressure distribution at material-die interface for improving the die design and service life has been performed by [5]. During the quotation process, an aluminium component was simulated using DEFORM-3D to evaluate pressure distribution. Several ductile fracture criteria with FE code gives critical damage value; has been used to predict successfully fatigue and fatigue crack growth in hot forging die with higher accuracy [14].

The comparison of the theoretical study and experimental test results indicates a potential for the developed model to be employed for predicting deformations and microstructure parameters. Mechanical fatigue, both by experimental data analysis and numerical simulation using Forge software for hot forging tool steels has been analyzed by [15]. Also, Comparisons had been made to evaluate numerical predicted life for laboratory fatigue tests and industrial forging tools.

Pro-E and Superforge softwares has been used in designing and modeling respectively, to predict the stresses appeared in die during hot forming of bevel gear by [16]. The result showed that the effective stress will increase with rising coefficient of friction and with increasing the temperature, the press force decreases and effective plastic strain increases. Initial stock size has been reduced; during fabrication of spindle by hot forging process, using Finite Element method (commercial FE-code Q-FORM 2D). Process parameters like effective strain distribution, material flow and forging load in different stages of the process were analyzed and concluded from the simulations that minor modifications of piercing punch geometry to reduce contact between the punch and emerging vertical walls of the cylinder appreciably reduces the piercing load. In the flange chamber, a die surfaces angle of 52° instead of 45° is proposed to ensure effective material flow and exert sufficient tool pressure to achieve complete cavity filling [17].

A new wear calculation model was proposed for optimal design of the mandrel geometry (as an example) based on the proposed wear calculation model (SEM studies), forging numerical simulation, BP neural network and Sequential Quadratic Programming (SQP) algorithm [18]. A real life automotive driveline component, a flange yoke, had been investigated by researchers using DEFORM 3D. The effect of selected input forging parameters on forging load along with heat generation due to deformation, heat transfer had been determined and coupled with the basic deformation analysis, so that the solution is close to the real life. The billet temperature, flash thickness and friction are found to have significant effect on the forging load. Among the three, the temperature of the input billet is found to be the most significant parameter followed by flash thickness and friction factor, in that order [19].

The analysis of the three-dimensional strain state for the forging process of the Ti-6Al-4V alloy using FEM, assuming the rigid-plastic model of the deformed body had been performed by [20] and reported the results of simulation studies on the metal flow pattern and thermal phenomena occurring in the hot forging process conducted on three tool types. The computation results enable the determination of the distribution of effective strain, effective stress, mean stress and temperature within the volume of the blank.

3.3 Forging Product Development

Due to higher customer expectations in terms more developed products, simulation techniques have been used to develop them with tighter tolerances, at a lower cost, and in less time. As an illustration, Simulation of the industrial forging process of a ball hook component was performed using the finite element software DEFORM-3D, following the thermo-mechanical procedures coupled with microstructure evolution by [21] has been taken here. The process parameters such as temperature, strain and strain rate and microstructure evolution during hot closed die forging has been studied. The geometry and grain size evolutions obtained by simulation were compared with those found in the actual process and are described in figure 2 to figure 5.

Figure 2. Workpieces during forging stages 1-6 (from left to right): 1-2: upsetting; 3: flattening; 4-5: die-forging; 6 final product after flash removal [21].
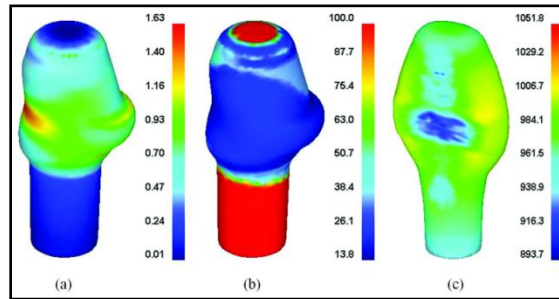
Figure 3. Simulation results: (a) effective strain distribution and (b) austenitic grain size distribution (µm) for the second upsetting stage and (c) temperature distribution (°C) for the flattening stage [21].
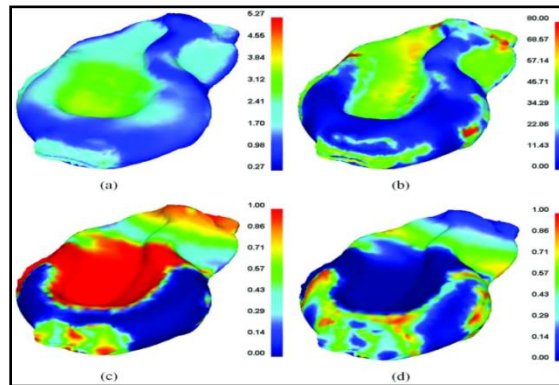

Figure 4. Pre-forging simulated results: (a) effective strain distribution; (b) strain rate distribution (s−1); (c) dynamically recrystallized volume fraction; (d) statically re-crystallized volume fraction after the inter-pass time of 5.2 s [21].

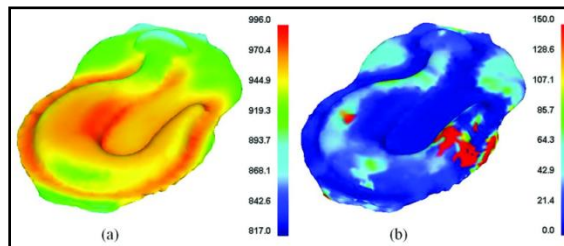Figure 5. Final-forging simulation results: (a) temperature distribution (°C) and (b) austenitic grain size distribution (µm)[21].

3.4 Forging Product Optimization

Connecting rod considered as forging product was optimized using finite element method based DEFORM 3D software in conjunction with Taguchi method in terms of metal flow in closed die. The optimal shape of the billet, based on forging load minimization, was obtained by performing a series of optimization iterations (Figure 6). The optimal shape of the billet that gives minimum forging load with complete die filling was obtained after several optimization iterations [22].
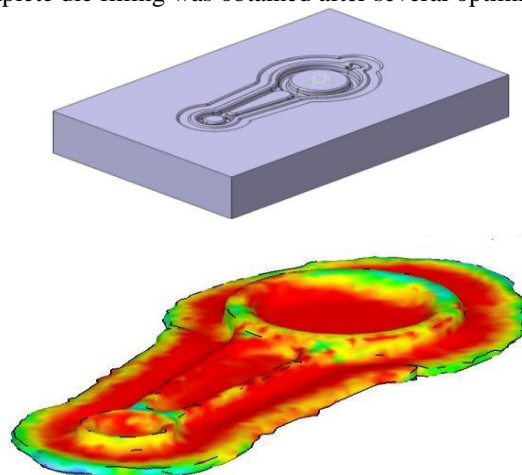
Figure 6. (a) Die of the connecting rod (b) Complete die filling with maximum forging yield and without any defect [22]
An automotive driveline component (Flange Yoke) was developed and optimized simulation methods (DEFORM 3D) for closed die hot forging process. The effect of selected input (forging) parameters on forging load is determined. The metal flow prediction, die filling prediction, billet temperature, flash thickness and friction had significant effect on the forging load. Among all, billet temperature was the most significant parameter followed by flash thickness and friction factor [23].

4. CONCLUSION

The simulation techniques have significant roles in closed die forging process development. Starting from process development to product optimization can be achieved by application of Finite Element Analysis techniques. The abrasive wear and plastic deformation in forging dies have been predicted and thus die life calculations can be predicted before start/in between of actual process. The effect process variables (temperatures, pressures, velocities etc.) to predict die wear as well as the stresses of the dies to predict the plastic deformation have been also predicted using FEM. FEM is also used to determine the flow stress of the die tool steel (which is not usually available in literature) using a limited amount of data, such as the ultimate tensile strength, yield strength, and hardness as functions of temperature (which is provided by the manufacturer). Whether it will be through changes in material (workpiece or die), press speed, operating temperature (of the workpiece or die), or die shape, FEM can be used effectively to improve the forming process. Thus, costly experimental work and die tryouts can be minimized with the use of FEM simulations to predict die life.

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