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Application of optimization techniques in metal forging- A review and reflection

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Abstract— Optimization of forging process is required to reduce the production cost of the die as well as the forged part and also to increase the accuracy of the die and the forged part. In metal forging process the performance of the die and hence product quality is heavily dependent on various parameters. In order to reduce the cost of forging process and make it competent with other production methods, it is essential to optimize these parameters that will facilitate a risk free manufacturing environment which can help to minimize the overall cost. In metal forging optimization problems, the interest is to produce quality products with minimum energy. A significant improvement in process efficiency may be obtained by process parameter optimization that identifies and determines the regions of critical process control factors leading to desired outputs or responses with acceptable variations ensuring a lower cost of manufacturing. Since the past few years computer aided engineering (CAE) techniques have been widely used for research in metal forging. Amongst them finite element analyses (FEA) have been greatly successful to provide the understanding of metal flow and die stresses for different forming processes. The present paper attempts a literature survey on the applications of finite element method (FEM), statistical tools and soft computing (SC) tools in metal forging processes.

Index Terms— Optimization, Finite Element Method, Statistical techniques, Soft computing, Expert system.

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1 Introduction

The degree of the structural reliability and high strength to weight ratio achieved in the forging process, make the forgings the best choice for high performance, high strength, high reliability and long term usage applications, where tension, stress, load, and human safety are critical considerations. Forgings are widely used in the automotive industry, defense industry, marine industry and aerospace industry, agricultural machinery, off-highway and railroad equipment, valves, fittings, petrochemical applications, industrial hardware and hand tools. In order to increase the die life and product quality so as to reduce the cost of forging process and make it competent with other production methods design activities need to systematically consider various design and process related parameters, and finally come out with the best parameter configuration for better process performance. However, the forming sequence of a new design is not a straightforward task, and it requires many trials and adjustments to achieve satisfactory production conditions. The empirical “trial and error” method has been traditionally applied to metal forming design; however, this approach is expensive and time consuming. Computer simulation has become reliable and acceptable in the metal forming industry since the 1980’s. Many researchers have worked on hot forging, this paper emphasizes on hot forging die and process design and hot forged part. Different authors made an attempt to optimize the die design and to achieve the quality of forged part, for that they have used different techniques, like Finite element method (FEM), Finite volume method (FVM), statistical tools like Taguchi method, factorial design, response surface methodology, etc. and soft computing (SC) tools like Artificial Neural Network, Fuzzy Logic and Genetic Algorithm etc.

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2 Literature Review

2.1 Fem used for modeling and analysis

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 possible alternative. Among other methods, the Finite Element Methods (FEM) is widely used in metal forging analysis due to its capabilities to model the complicated shapes of dies and parts in forging processes. FEM (Finite Element Method) has been adopted by many researchers for optimization of die design and die design process. This tool has been used to perform analysis of the die design parameters, and to get the accurate results without damaging any physical structure. The physical structure can easily be modeled in CAD package and then can be transferred to FEA package where the various analyses can be done. To optimize the product, one can easily change the geometry in CAD model to get the optimize geometry. Similarly the material properties also can be change. The researchers have excellently used these tools for the simulation. Many researchers made an attempt to give the solution for problem using the FEM, like “Santos et al. [1] utilized the FE method to determine the size of initial material of workpieces and the forces that to be implemented. The authors have been discussed that the numerical simulation could in fact assist modification and hence reduce trial and error stage in preparing the tools for forging process. FE method may also provide an important answer in predicting the process and defects". "Satish et al. [2] uses FEM-based computer simulation to optimize the design parameters and input billet cross-section for front axle beam. By carrying out multiple number of forging experiments during simulation trials, input billet size has been optimized". "Gangopadhyay et al. [3] uses three-dimensional finite element analysis DEFORM 3D software on multistage hot forming of railway wheels involving the processes of upsetting, forging, and punching of wheels". "Kadir, Ab et al. [4] highlighted that a small corner and fillet radius would introduce high stress concentration resulting in increase in die wear and small value of friction coefficient is desirable for uniform deformation of workpiece and improving die life by using FEM-code DEFORMTM F3 v6.0". "Desai et al. [5] study the design parameters of gear forging using finite element method (FEM) and found that several parameters such as shear friction factor, punch velocity, aspect ratio and temperature on die will affect the quality of the forged gear". "Srivastava et al. [6] studied the effect of billet temperature, die velocity and coefficient of friction on forging load and strain rate by using FEM based FORGE2R". "Debin Shan et al. [7] developed a three-dimensional rigid-plastic finite-element method program to simulate the isothermal forging of the cylindrical housing. They found that the finite-element method is an effective tool for the numerical simulation of forging process". "C.H. Yu and J.J. Sheu [8] studied the different installation positions of punch, preforms, and profiles of punch tip and tool configurations to obtain the die stress distributions and predict the die failure of the orbital forging process by using FEM simulation". "Kang et al. [9] presented preform shapes design in forging of rib-web shaped plane-strain parts by using rigid-plastic finite element method in order to obtain flash-less parts". "Lee et al. [10] have performed a study to evaluate the dimensional differences between forged components and forging die by using FE method as well as experimental data". "Choi et al. [11] study the effect of process parameter of round shape product focusing on feed rate and rotation speed angle for optimal forging pass design based on FEM result". "Liwen Zhang et al. [12] simulated an entire forging process of a gas turbine compressor blade from a cylindrical billet to a complicated product, using 3D rigid-viscoplastic FEM. They verified the simulation results through comparisons with industrial trials, which were conducted on the same process parameters as those in the simulation". "W. L. Xu and K. P. Rao" [13] have carried out an analysis of isothermal axisymmetric spike forging using an integrated FEM code. Simulations have been conducted to investigate the influence of different geometric parameters, processing variables and interfacial conditions on the instantaneous spike height". "Abbas Ghaei and Mohammad R. Movahhedy [14] used a 3D finite element model to simulate the Radial Forging of tubes both with and without mandrel. Then, the model was used to study the effects of cross-section shape of hammer die on deformation in the Radial Forging process (RFP)". "T. Takemasu et al. [15] developed a perform optimization methodology of connecting rod forging by using 3D FEM simulation and physical modeling experiments". "Campos et al. {16] analyzed the failure by excessive plastic deformation of the high relief ring in the bottom die during the third stage of a gear blank forging using a finite element method.

2.2 Application of statistical techniques and soft computing tools in forging

Traditional engineering design optimization is the process of identifying the right combination of product parameters which is often manual, time consuming and involves a step by step approach to identify the right combination of the product and associated process parameters for the best solution. Often the manual approach does not allow a thorough exploration of the solution space to find the optimum design, resulting in sub-optimal designs. With increasing global competition, it is necessary to design products that are able to satisfy human needs in the most effective manner. Since the design of product and tooling is affected by many factors and there are many design variables to be considered, the combination of those variables comes out with various design alternatives. It is thus not pragmatic to simulate all the designs to find out the best solution as the coupled simulation of non-linear plastic flow of billet material and tooling deformation is very time-consuming. One of the limitations of numerical simulations is still the high computational time for complex parts, despite the development of iterative solvers, fast contact algorithms and the ever ongoing progress in computer hardware. The statistical design of experiments (DOE) and soft computing (SC) tools are used to effectively address various problems and issues related with metal forging processes with minimum number of experiments. The major applications of these DOE and SC tools can be broadly classified into the areas of design, optimization and prediction of forging processes. The various metal forging processes that are found to use these tools are in design of dies, performs and forging tools, optimum force calculation, predictions of several effects like springback, tool/die failures etc. Design of experiment (DOE) techniques like the Taguchi method, the response surface methodology, etc. can optimize process parameters with minimum experimental runs. The objective of soft computing (SC) tools like Artificial Neural Network, Fuzzy Logic and Genetic Algorithm etc. is to accommodate imprecision, uncertainty, partial truth and approximation etc. Enormous amount of research has been conducted for determining optimal process parameters by using these tools in various forging processes. "Kim, D.J. et al. [17] have used neural networks and the back-propagation algorithm to determine the initial billet geometry for the forged products using a function approximation". "Sedighi et al. [18] studied a combination of neural network and genetic algorithm for optimization of the preform in close die forging of an Aeronautical forging component". "Miaoquan, L. et al. [19] established a new model coupling the fuzzy set with the artificial neural network theory for microstructural evolution of isothermal forging of Ti–6Al–4V titanium alloy for the quality control of the thermal deformation process. "Ko, D.C. et al. [20] suggested a new method of preform design in multi-stage metal forming processes considering workability. The artificial neural network and the Taguchi method have been implemented for minimizing the objective function and for investigating the effect of process parameters relevant to the process". "Duggirala et al. [21] uses an adaptive micro genetic algorithm to minimize the possibility of the initiation of tensile fracture in the die in cold forming process by optimizing preform parameters. Significant reduction in the maximum damage value was achieved as a result of this optimization process". "Toro, Luis et al. [22] developed a fuzzy inference system to predict the grain size resulting from the upsetting of IN718 alloy". Ohdar, R.K. et al. [23] developed a neural network and a neuro-fuzzy model for predicting the behaviour of Ti-6Al-4V alloy under isothermal forging condition, and analyzing the relationship between temperature, strain rate and strain with the flow stress". "Biglari, F.R. et al. [24] used a backward deformation method in combination with a fuzzy decision making approach to predict the shape of the workpiece at each backward time increment. It was shown that the backward deformation method in conjunction with the fuzzy logic algorithm leads to a more uniform plastic strain in the simulated final component". "C.Y. Park and D.Y. Yang [25] analyzed the void-crushing process, including the bonding process by the finite-element method for three-dimensional forging at elevated temperature. The effects of the pre-cooling temperature, the rate of deformation and the change of the die-shape are discussed for obtaining the high crushing efficiency of a void, using the Taguchi method". "He, X. et al. [26] proposed a robust parameters control methodology based on Taguchi method and numerical simulation to control microstructure of heavy forgings". Tang, Y.C. et al. [27] developed a preform tool shape optimization method by using response surface method (RSM) along with neural network approximation model in order to overcome the limitation of quadratic polynomial model in solving non-linear problems in a two-step axisymmetric forging problem". "Sanjari, M. [28] employed the artificial neural network (ANN) and the Taguchi method to optimize the radial force and strain inhomogeneity in radial forging process". "W.L. Chan et al. [29] developed an integrated FEM and ANN methodology to approximate the functions of design parameters and evaluate the performance of designs in such a way that the optimal design can be identified". "Lee et al. [30] proposed an approach for finding a preform shape in axisymmetric hot forging by using the equi-potential lines in the electric field and the artificial neural network. The perform shape is determined among the equi-potential lines obtained between the initial and the final shape". "Tercelj et al. [31] used neural networks with FE simulation for the prediction of wear on die radii during hot forging". "Repalle et al. [32] adopted response surface model to establish a relationship between the process performance and the critical process variables and an automotive-component forging-process design was presented to demonstrate the applicability of the method. "Y.C. Tang et al. [33] proposed a preform tool optimization method based on response surface methodology technique along with neural network-based response surface and optimal preform tool shape is achieved by searching for the optimum of the surface using pattern search algorithm". "M. Zamani et al. [34] examined the wear profile on the die surface during the hot forging operation for an axisymmetry cross section. The amount of wear was calculated for two wear model by implementing a rigid thermo-viscoplastic finite element analysis. Finally the influence of friction on the amount of die wear and material flow was discussed". "S. Serajzadeh [35] developed a hot forging model by coupling a thermo-mechanical analysis based on a two dimensional finite elements and a neural network model. The neural network was used for prediction of the flow stress behavior of metal being deformed as well as determination of heat of deformation for the thermal analysis". "Su-Hai Hsiang and Huey-Lin Ho [36] adopts the finite element method (FEM) and the artificial neural network (ANN) to yield the optimal designed die of radial forging of work-hardened materials". "Jeong et al. [37] used the fuzzy system and the forward projection to predict the initial billet shape which satisfied the die filling". "D.J. Kim and B.M. Kim [38] proposed a new technique to determine the initial billet and to design the die geometry using a function approximation in neural network and the F.E. simulation, which satisfy the full-filling of the die cavity for axisymmetric hot forging and the same height of the inner rib and the outer one for cylindrical pulley". "M.H.Sadeghi et al. [39] investigates the effect of flash thickness and various geometrical forging design parameters including internal and external drafts and internal and external corner radii, on the die cavity filling, forging load and raw material cost when forging Nimonic80-A superalloy by using DOE-designated fractional factorial and FE simulations. Also a response-surface-methodology (RSM) based method for forging load prediction is presented". "F.C. Lin et al. [40] presented an abductive network in conjunction with Taguchi method to predict the minimum additional material volume of preform billet for an acceptable product without shape defect such as unfilling in closed-die forging process". "D.C. Ko et al. [41] describes a new method of preform design in multi-stage metal forming processes considering workability limited by ductile fracture. The finite element simulation combined with ductile fracture criterion has been carried out in order to predict ductile fracture. The artificial neural network (ANN) using Taguchi method has been implemented for minimizing objective functions relevant to the forming process". "Roberts et al. [42] integrated ANN with Gaussian processes (GP) to estimate the cracking pattern of aluminum metal matrix composites in forging. They then used FEM to calculate the stress and strain in the composites, and compared the two sets of results". "Trowsdale et al. [43] used ANN to develop a real-time analytical system and further analysed the stress and strain relationships of the open die forging". "Kim et al. [44] used the three-layered ANN pattern to analyse the cold forging of a cylindrical pulley, to determine the relationship between the design of the initial billet and the fullness of the die cavity".

2.3 Development of an integrated system

Development of an integrated system to be used in assisting the forging designer has great potential in die design. To date there are several systems that have been developed. "Jolgaf et al. [45] developed a system that can simulate and optimize the die design and based on the result, a machining code is produced using available CAM software and then fabricate using

CNC machine. The integration between CAD and CAM tools can be utilized in the manufacturing process for economic production". "Yang et al. [46] and Srinivasan et al. [47] constructed a larger scope system where they also integrate the rapid prototyping (RP) technology to demonstrate the physical model of the process at different stages. The technology can also consider the process characteristics such as geometrical complexity, effects of the process parameters, flow pattern of work piece, deformation induced defect and etc. In this research, the deformed shape at different processing stages is physically presented by converting CAE data into file format that can be read by RP system (i.e., stl format)". "Fujikawa [48] applied the FE simulation to study the design parameters for the crankshaft forging process. Eight factors concerning the material filling performance, forming load and the material quantity were selected. In order to reduce the number of simulations, orthogonal array was employed to determine the critical design combination. By using his proposed approach, he claimed that the development cost could be reduced by 40% when compared with the conventional trial-and-error approach". "Su-Hai Hsiang and Huey-Lin Ho [49] integrates rigid-plastic FEM with the ANN to plan the radial forging of work-hardened materials to yield the optimal designed die". To support the design of the whole metal-forming system, "Fu et al. [50] proposed a simulation-based approach to assessing the design of metal-forming system. Based on their study, an integrated simulation framework for supporting metal-forming system design was proposed and various design factors relating to the quality of metal-formed product were articulated. The design index was also proposed to evaluate the performance of different forming system designs and finally the optimal design was identified". "Lee et al. [51] developed a parametric computer-aided tool design system for cold forging using AutoLISP". "B.T. Lin [52] presented a knowledge-based parametric design system for drawing dies which requires only a minimum set of parameters to be set before it is able to complete the design of the main components of a die, such as upper dies, lower dies, and blank holders. This minimum set of parameters includes blank sizes, die faces, punch open lines, drawing strokes, and press data. This design system implemented on top of the Pro/E CAD software consists of a drawing die knowledge base, a subcomponent inferencer, a dimension calculator, a subcomponent generator, a system coordinator, and a user interface". "T. Perus et al. [53] presented a new approach which combined the use of a conditional average estimator neural network (CAE NN) with the exploitation of results obtained by the finite element method (FEM) and also data from other sources for prediction of tool wear in hot die forging along the entire arbor radius".

2.4 Development of an expert system

An expert system is a tool that has a proven database which was constructed using case base experienced by the experts in the industry. An expert system is developed to help less experienced designer in making decision. In forging process, recommendation from an expert system can help in ensuring that productions are at the most optimal quality and economic values. The ESs can produce results in real-time (almost instantaneously), which even the shop-floor people can use for effective decision-making. In developing an expert system, there are two types of approach used, knowledge-base and rule-base [54]. There are many researchers that tried to solve the problem occurs and suggest the best alternatives for forging condition. "Katayama et al. [55] developed an ES for the design of cold forging process using a case base as the knowledge base and the fuzzy pattern matching as a reasoning theory". "Park et al. [56] designed a fuzzy logic-based ES to estimate dimensional errors of constant velocity (CV) joint ball groove for the precise control of forging operation. They used the measured sensor data of CV joint ball groove to generate the data base". Recently, "Subba Rao and Pratihar [57] developed a GA-tuned fuzzy logic-based ES for predicting the deformed geometry of compressed rubber cylinder between flat platen. The variations of FE output with the element shape and size were studied in their work. The developed ES could predict the FE simulation output within a fraction of a second with reasonable accuracy". "Kim et al. [58] developed an expert system to automate the process design of axisymmetric hot steel forging. The system can be used to design the geometries of the finisher, blocker, buster, billet and corresponding dies, and to calculate the required forging load, the volume and the strokes, based on the geometry of the product. It is a rule-based system developed in Fortran and AutoLISP and operated in AutoCAD environment". "Kim et al. [59] developed an automated computer aided process planning system for a hot forging or blanking product by press working. The system is based on knowledge-based rules, and a process knowledge base of design rules is built". "Choi and Kim [60] established knowledge-based design and CAPP system for cold and hot forging, the rules of hot forging and cold forging are collected in this paper". "Caporalli et al. [61] developed an expert system for hot forging design, the software ADHFD (automated design of hot forging die). This software was used to design flashless hot forging die of gear". "T. Gangopadhyay et al. [62] developed fuzzy logic-based expert system to predict forging load and axial stress developed. They found that the expert systems are able to make predictions of forging load and axial stress as accurately as the FE package can do.

3 Conclusion

In this paper an attempt has been made to present a review of the applications of various optimization techniques in metal forging. Optimization of forging parameters has been done by many authors using different techniques excellently. FEM (Finite Element Method) has been adopted by many researchers for optimization of forging design and process parameters. This tool has been used to perform analysis of the die design parameters, and to get the accurate results without damaging any physical structure. Although the simulations based on the FEM method are capable of predicting many variables such as forging load, strain, strain rate and stress distributions more accurately, but those are time consuming and computationally expensive for a completely optimization procedure. Design of experiment (DOE) and soft computing tools has been identified as useful tool to design and analyze complicated forging problems. Statistical design of experiments (DEO) tools is used to study a large number of variables with a small number of experiments. These tools can also be applied to investigate which parameters influence the forging process most significantly. DEO Tools can effectively establish optimal parameter settings for single performance characteristic. When multiple performance characteristics with conflicting goals are considered, the approach becomes unsuitable. For multi response optimization recently, some researchers have used genetic algorithm, data envelopment analysis, desirability function approach etc. soft computing tools are used to exploit the tolerance for imprecision, uncertainty, partial truth and approximation to achieve tractability, robustness and low solution cost. The principal constituents of soft computing are Fuzzy Logic (FL), Neural Computing (NC), Evolutionary Computation (EC), Machine Learning (ML) and Probabilistic Reasoning (PR). Expert Systems can produce results in real-time (almost instantaneously), which even the shop-floor people can use for effective decision-making. From the existing literature it can be observed that the major applications of these tools can be broadly classified into the areas of design, optimization and prediction of forging processes. The various metal forging processes that are found to use these tools are in design of dies and preforms, forging load and die stress calculation, die filling prediction etc. during forging.

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