A Review on Modelling, Design and Optimization of Forging Process

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Abstract. Forging is a core manufacturing process. It gives a product of superior mechanical properties and produces minimum wastage of material. This makes it a better manufacturing process as compared to other processes like casting etc. An aligned grain flow defines a good forging. The effectiveness of a manufacturing process is characterized by low cost, high productivity and high quality of product. This necessitates the use of three dimensional computer graphics and powerful Computer Aided Engineering (CAE) software to analyze the forging process. The present paper discusses on the various research works carried out in different fields of forging. The scopes of further researches on different problems of forging are also elaborated.

Keywords: FEM; FEA; DEFORM; Forging; Optimization technique.

1. Introduction

Forging is one of the most useful metal working process by which one can easily give a metal work to a useful shape through dies & tools. The process consists of hammering or pressing the metal object. The steps of forging are shown in flow chart form in fig.1. It is one of the oldest and useful metal work methods whose origin can be found on about some thousands of years back. Forging process produces high degree of structurally reliable and strength to weight ratio products, which make it one of the most suitable manufacturing processes to be considered for production of product with high strength and long-term usages. To reduce the cost of forging process, the method should be designed in such a way that best parameter set can be used for producing better quality (high strength & high reliability) products as compared to other production methods. But establishing a sequence for new product design is not as simple as machining process. It requires a lot of trials & errors to produce a satisfactory product set up. Empirical trail & error method is widely used for forging process, but it is very time consuming and costly method. With the availabilities of highly efficient numerical techniques like FEM, FEA etc., the computer simulations are used to test the performance of the manufacturing processes. With the advancement of analysis techniques like the finite element method (or analysis) (FEM (or A)), computer simulation was introduced in early 1980’s as a possible alternative. Many successful attempts have been made to optimize the die design and to produce better quality forged part. Various techniques are adopted in literature like Finite Element Analysis (FEA) [2, 3, 4, 7, 9, 11, 13, 15, 16, 17, 19, 20, 23, 24, 27, 32, 33, 35, 38, 49, 52, 53, 54, 65, 66, 67, 68], Finite Element Method (FEM) [1, 6, 8, 10, 14, 21, 30, 31, 43, 50, 64, 69], Finite Element Modelling [60, 63], Taguchi Method [23, 61], Grey Taguchi Method [20], Rigid Plastic (Rigid Visco-plastic) Method [4, 14, 27], ANOVA [22, 39], Dynamic Recrystallisation (DRX) Model [6, 13, 31, 56], Serve Plastic Deformation (SPD) [25, 30, 32], Response Surface Method (RSM) [29, 39, 47, 63], Equal Channel Angular Pressing (ECAP) [32, 38], Equal Channel Angular Extrusion (ECAE) [30, 34], Latham and Cockcroft Formula [12, 57], Monte Carlo Method [5, 19], Pseudo Inverse Approach [18], Archard Wear Theory [2], Johanson-Cook Type Material Model [8], Slab Method [69] & soft computing tools like ANN (Artificial Neural Network) [5, 62], Genetic Algorithm (GA) [29, 62], etc. Among these methods, FEA is widely used in metal forming analysis.
due to its capabilities to model the complicated shapes of die and parts in forging process. FEA has been adopted by many researchers for optimization of die design and die design process. Lee & Jou [2] utilized the FEA combined with Archard's Wear Model to explain the wear mechanism in warm forging. Wear amount is predicted in outer race of automotive transmission in design stage of warm forging die. Lv et al. [4] utilized FEA to explore the complete information of forging process like material flow in die, forging load, strain in forging, die temperature etc. Lu et al. [9] utilized the FEA combined with Dynamic Material Models (DMM) to work on the hot forging process (HFP). In this work, author predicted the distribution and variation of deformation zones in external HFP and also determined & optimized the parameters of external HFP. Hino et al. [15] used FEA for developing a design methodology, which is used to reduce the number of stages in multistage forging process. Equbal et al. [20] used FEA combined with Grey Taguchi Method and ANOVA Method to optimize the forging load and billet temperature loss individually and also find the significant parameters. Christiansen et al. [23] applied FEA combined with Porous Plasticity Models to forecast and optimize V-shaped angled lower die. Salcedo et al. [25] used FVM to predict different die design configurations for the isothermal forging of cam. Different aspects of forging techniques like modelling, design and optimization of forging processes are discussed in different subsections.

Fig. 1 Flow Diagram of Forging Process
Rests of the paper are organized as follows. In section 2, the main works on modelling, optimization and design are discussed. In section 3, a brief discussion is made on the reported works to outline the future directions of researches on forging processes. Concluding remarks are made in section 4.

2. Literature review

The research works carried out on forging can be classified into different categories based on types of researches like modeling and simulation of process, optimization of process, materials and design of process, etc. The different techniques used, the modification done, case studies & results observed on these areas are being outlined in different subsections.

2.1. Modelling and simulation

Viability of modelling and simulation is very important to the industrialists. Many researchers have used DEFORM software (finite element based) for performance analysis of forging processes through simulation. The steps of simulation are shown in flow chart form in fig. 2. Li et al. [1] utilized the FEM, Lagrangian method, PM (Penalty Method) & SIM (Selective Integration Method) to material flow, heat transfer, forming equipment response to the work piece, die stress and die deflection. Lee & Jou [2] calculated the wear velocity and also predicted the die life in warm forging using Archard’s wear model and FEA. Then FEA combined with modified wear model and experimental data is used to calculate wear amount of automotive transmission design stage. Lv et al. [4] utilized the FEA combined with 3D rigid-Viscoplastic FEM to improve the quality of gas turbine compressor blade. Sun et al. [5] utilized the Artificial Neural Network, Monte Carlo Method, Cellular Automata (CA) Method and Empirical Models to analyze the deformation behavior for optimization of deformation process of TA15 titanium alloy by micro-structure evolution model. Ding et al. [6] utilized the constitutive equation and dynamic recrystallisation model combined with FEM to work on the manufacturing of AM50 alloy sheet and obtained a uniform micro-structure with moderate recrystallized grain size. Multi-pass hot rolling (rapid roller speed) is recommended for this process at a high temperature. Zamani et al. [8] utilized the FEM, Johanson-Cook Type Material Model and Lagrange Mesh Formulation to reduce tool wear and increase tool life by the assistance of the laser. Also, by the application of optimization of both laser and machining parameters, forces are reduced significantly. Lu et al. [9] utilized the FEA and Dynamic Materials Model (DMM) to analyze and optimize the unstable deformation in hot forging process parameters and finally resolved the unstable deformation.

Equbal et al. [10] utilized the FEM and Thermo Mechanical Simulator (GLEEBLE-3500) to analyze the deformation behavior of die/work piece interface. Hot compression experiment and FE simulation are found to be more effective means to study deformation behavior. Yukawa et al. [11] utilized the FEA, Compression Test and Oxide scale thickness Method to analyze and understand the heat transfer coefficient and different contact pressure in a function of thickness of three oxide layers. Gisbert et al. [13] utilized the FEA, slab method, ring compression test, shear friction model and coulomb friction model to develop an analytical model in bimetallic ring cylinder assemblies for evaluating the forging load. Also, coulomb friction model combined with above approach, two new analytical models developed for a better simulation and nearer to the actual problems. Ou et al. [3] utilized the ABAQUS software combined with finite element analysis to study the aerofoil cross-section of forging. In this study, authors found that aerofoil thickness error was mainly due to die elasticity, aerofoil bow, twist error and press deflection. Afazov et al. [7] utilized the FEDES combined with FEA, NPM (Nearest Point Method), Distance method using the elements, ESFM (Element Shape Function Method),
Distance method using field of point to explore and understand the FEDES (Finite Element Data Exchange System). It is found that FEDES can be very useful for the simulation of manufacturing chains. Kakimoto & Arikawa [12] utilized the Forge-2D & Forge-3D combined with Numerical simulation (By Latham & Cockcroft formula) and High Temperature Tensile Test to analyze the surface cracking. It is found out that surface cracking prediction is by the numerical simulation based on temperature, strain rate and fracture parameters. Also, damage parameter critical value is calculated by numerical simulation (based on the result of reduction in area).

![Flow Diagram of Simulation](image)

2.2. Optimization

Optimization is the process of making the best or most effective use of a situation or resource. Optimization is very important for forging processes to make the process efficient. Many researchers worked on the optimization of forging techniques in recent pasts. The steps of Taguchi method are shown in flow chart form in fig. 3. Choi et al. [14] utilized the DEFORM software combined with FEM (3D-Rigid plastic) to work on the feed rate and roundness in bar. It is found that roundness in bar depends on rotational angle. Also, feed rate balances the quality of product and productivity in forging. Hino et al. [15] utilized the FEA to develop a new design method. This design method is important for multistage forging process to reduce the numbers of stages. This method is also applied to the other metal forming processes like multistage deep drawing. Recker et al. [16] applied the FEA
to analyze the microstructural properties. The study gives a rough, quick approximation of properties and quality of work piece in the process. Also, surface temperature is measured at the respective location. Cheng-Liang et al. [17] utilized the FEA and Orthogonal experiment method combined with DEFORM software to improve the process design and design variable like width of rib, thickness of rib, length of rib and inclination of rib. Halouani et al. [18] utilized the Pseudo inverse approach (PIA) and B-spline curve to explore the preform design. It is found that, to optimize preform design and respective parameters, simulation approach is much faster than the incremental approach. At the optimum preform shape, modified parameters improve the objective function. KroiB et al. [19] applied the FEA and Monte Carlo method to work on the interaction between process design, tool and machine in cold forging process. To achieve high work piece accuracy, optimized value of influencing parameters like work piece dimensions and forging load should be used. Equbal et al. [20] used the FEA, Grey Taguchi method and ANOVA method combined with DEFORM software to analyze the process parameters e.g. billet temperature and forging load. It is found that low billet temperature & low forging load are significant. Zhang et al. [21] applied FEM combined with Taguchi method to explore the precision forming process. It is found that strength and toughness of forging (rib-web forging) increased and utilization of material is improved by this precision forming process. Rib-Web forgings are obtained by multiobjective design process. Bai & Yang [22] used the vibration-assisted micro forging combined with ABAQUS software to optimize better metal foil surface finish due to large vibration amplitude and low initial static stress. Christiansen et al. [23] utilized the FEA and Porous plasticity model to optimize the V-shaped angled lower dies (Lower die angle in the range 90-120 degree ensures best result) in ingot forging.

![Flow Diagram of Taguchi Method](image-url)

**Fig. 3 Flow Diagram of Taguchi Method**
Chval & Cechura [24] applied FEA to improve the technical parameters of mechanical forging process. In this study, authors found that stiffness increased by 7.5% and weight reduced by 10% by the application of this new approach. Stiffness and weight both are essential technical parameters for increasing accuracy and reducing cost of production of the process in the forging process. Salcedo et al. [25] utilized the FVM (Finite volume method), severe plastic deformation (SPD) process and Cockcroft Latham’s method to complete die filling, minimum imparted damage, minimum required forging force, maximum accumulated plastic strain & found that complete die filling is better in two stroke than one stroke forging configuration. Wang et al. [26] used the High temperature low-cycle fatigue (HTLCF) method to show that innermost layer is the best fatigue resistance performances, while the shortest HTLCF life was observed at the outermost layer for the same condition. The distribution of grains was more homogeneous and the content of δ-phase along the grain boundary was lower at the innermost layer.

2.3. Material and design

Material and Design is another important area of forging researches. Many researchers worked on the material and design of forging processes for better quality products. The steps of general forging design process are shown as flow chart form in fig. 4.
Deng et al. [27] utilized the FEA (3D-FE model) and ring compression test combined with DEFORM software to optimize the spur bevel gear geometry. Lower forming load and better filling of gear shape are analyzed by numerical simulation. Finite element analysis helps to determine the following detailed information like forming load, effective strain, forming panorama, and metal flow combined with process design. Kaynar et al. [28] used the OM (Optical Microscopy) & SEM for determination of final microstructure and mechanical properties (like hardness and tensile test). Authors also analyzed the following microstructural compounds such as coarse precipitates, ferrite and pearlite. Lee et al. [29] utilized the Equivalent static load (ESL), Design of experiment (DOE), Response surface method (RSM), Backward tracing method, Sensitive analysis method and Genetic algorithm (GA) to optimize the work piece shape. Post-process in the forging is not required for the flash removal and found that forging produces fine quality products. Puertas et al. [30] used FEM combined with SPD and ECAE to explore and understand the Francis turbine blade design. In this study, Francis turbine blades are manufactured by AA1050 (micrometric microstructure). It is found that mechanical properties are better in comparison to conventional forging. Also, moderate forging temperatures are required in comparison to conventional forging. Suressh et al. [31] applied FEM, Dynamic recrystallization (DRX) Model and Inter-crystalline cracking combined with DEFORM software to study the development of microstructure. For estimating the local & average strain rate in forging envelop, FE based simulation is used. At high speed & low temperature, material flow is localized and hence changed microstructure in forging. Perez et al. [32] used FEA combined with SPD and ECAP to improvement in forging ability and micro-hardness and decrease in material grain size. For achieving mechanical component with no cracks & high hardness, pre-processing of ECAP is not carried out due to combination of low temperature of forging & ECAP. Bagherpour et al. [33] used the FEA combined with DEFORM software to optimize maximum angle of inclination that is higher in the fixed inlet channel die. For achieving maximum inclination angle, minimizing the power (for given friction factor) & maximizing the angle of distortion are applied. Jiang et al. [34] used the ECAE, SEM, OM & EBSD (Electron Back Scatter Diffraction) combined with DEFORM, TEXEVAI software to analyze and explore the microstructure of β-Mg17Al12 and found that eutectic network completely disappears in fine Mg-alloy particle and non-based texture stay stable. It shows that good balance of strength and ductility. To optimize the grain size, texture and morphology of eutectic network, MDIF combined with heat treatment is applied. Ozturk et al. [35] used FEA combined with ANSYS software to work on the design and manufacturing aspect of product in cold forging. For minimizing the total cost of cold forging parts, authors developed a concurrent design optimization method, which is related to the design and manufacturing parameters. Li et al. [36] utilized the OlympusGXSI optical microscope, ZEISS Evo 5.0 SEM & ED X-ray spectroscopy to explore the magnesium alloys from AZ91 alloy (weight reduction). For increasing the ignition point (above 800°C) and its strength & elongation, 2% calcium is added in the AZ91 alloy after liquid forging and extrusion. Ghosh et al. [37] utilized the EBSD (Electron Back Scatter Diffraction) & TEM (Transmission Electron Microscopy) to improve the mechanical property combined with high ductility and micro-structure of Nb–Ti stabilized IF steel by multi-axial forging process. Fuertes et al. [38] applied FEA and ECAP to analyze the mechanical property of aluminum alloy such as AA1050 (low value of strain hardening). To increase in hardness of a connecting rod, it is manufactured from ultra-fine-grained material and found that hardness is increased by 20%. Balta et al. [39] utilized the CDFW (Continuous Drive Friction Welding), RSM and ANOVA to explore the mechanical properties like tensile strength, elongation & petal crack length of weld. In this study, error (predicted value – measured value) are found 1.06% for
tensile strength, 13.37% for elongation and 2.44% for petal crack length and hence weld quality predominantly depends on tensile strength. Also, weld quality is identified by petal test.

3. Discussion & Future Directions

The main perspectives of manufacturing goods are quality of product, minimizing the cost of product, the lead time, and the manufacturing defect. For defect free manufacturing with minimum load, preform design, optimum die design and process parameters should also be included.

The most of the researchers have utilized finite element analysis for the examination of forging operation. It is more advantageous over other methods of analysis like archard wear theory, dynamic recrystallization method, nearest point method, Johanson-Cook type material model, slab method, pseudo inverse approach, compression test method, etc. due to the fact that FEA gives near net shape products. The advantages of FEA is that it gives detailed information about the different properties in computer screen. So one can decide about the system easily without testing on real products. So it saves a lot of effort and time. It simulates many things such as work piece & tool temperature, material property dependent on strain rate, deformation heat transfer, capabilities & characteristics of strain hardening for analysis of microstructure.

Many researchers worked on different aspects of forging process. Li et al. [1] focused on the verification of material parameters like flow stress, strain and temperature to analyze the transfer of heat, equipment of forging & flow of material. But other aspects like robustness, computation effects are not studied. Further research on forging should be focused on the improvement in robustness, computational efficiency, user-friendliness, graphics and post-processing techniques. Also focus should be on microstructural analysis such as size of grain, transformation of phase, fracture & precipitation. Ou et al. [3] worked on process and design parameters to minimize the forging error, defects, total cost and material loss. Further investigation should be done on improving optimization system using multi-weighing factor scheme to reduce forging error. Sun et al. [5] worked on rate of dislocation density, the size & recrystallization of primary α- grain process to analyze the distortion behavior and optimize deformation process of TA15 titanium alloy by micro-structure evolution model. The work was conducted only on two phase regions. Further research should be focused on multi-phase region to improve the result. Hino et al. [15] worked on process and design parameters of forging process to develop effective tool for the reduction of the number of stages in multistage forging process. The developed technique can be applied for envisaging the other metal forming processes such as multistage deep drawings.

With the advancement of technologies, forging industry is becoming more energy efficient and environment friendly. This makes it a very valued and responsible manufacturing process as compared to other similar processes. In next decades, forging will be zero liability and source of high paying jobs for employees in surrounding areas. So, virtual environment of forging is an important area of research, which can be examined.

Other specific areas where upgradation of technology is needed are process controls & sensors, software, process modeling & optimization, die design & die modeling, lubrication, maintenance in real time, and equipment of primary & secondary processing etc.
4. Conclusion

Many research works have been done to improve quality of manufacturing goods, minimize the cost and lead time, defect free forging etc. mainly through the use of FEA. This method is very beneficial for optimization process, predicting defect, analysis of die, forging load etc. Many researchers confirmed the result of FEA. In addition to FEA, so many other methods like Archard wear theory, Dynamic recrystallisation method, nearest point method, Johanson-Cook type material model, Taguchi method, Compression test method, Slab method, ANOVA method, Design of experiment method etc. are used in literature. The results are used to minimize the cost, increase the product quality, reduce cycle time & shop floor trail and remove defects. A few researchers have also worked upon Tribological properties of forged part – Wear, Tensile strength, Toughness and Hardness. FEA is a very useful tool for forging as it requires least effort for flawed die design or erroneous process plan. The researches have also been done on the control of the virtual environment of forging like damage model. This is a very important area of researches, which can be examined. Further improvement in efficiency of computation, graphics & post processing methods, robustness, and user & environmental friendliness are needed. Different aspects of current and future research scopes in the field of forging are also discussed.

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