Optimization of Forging Parameters to Improve Mechanical Properties of Steel Components

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ABSTRACT

Forging is a common metal forming process that heavily improves the mechanical properties of parts by enhancing grain refinement and structural integrity. In this investigation, the goal is to maximize important forging parameters like deformation temperature, strain rate, and die geometry to obtain improved mechanical performance in medium carbon steel parts. Both experimental trials and finite element simulations were utilized to analyze the effect of these parameters on tensile strength, hardness, and microstructure properties. Taguchi method and ANOVA test were used to analyze the optimal parameter settings. The outcomes show that controlled high-temperature forging and moderate strain rate coupled with optimized die curvature produce better grain flow, lower porosity, and better mechanical properties. This optimization not only improves the quality of forged components but also saves material and energy in the forging process. The results of this work are also specifically pertinent for automotive and industrial uses where strength and toughness are essential.

I.INTRODUCTION

Forging is among the oldest and most efficient manufacturing techniques for the production of high-strength components. The process entails the compressive plastic deformation of metals, utilizing hammers or presses, to deforme the material into a desired geometry. Differently from casting or machining, forging enhances the mechanical properties of the materials through grain flow alignment with the component shape, enhancing strength, toughness, and fatigue life [1]. It is because of these benefits that forging finds extensive application in major industries like automotive, aerospace, railway, defense, and construction.

Steel, especially medium carbon steel, is widely used as material in industrial forging processes due to its balanced mix of strength, wear resistance, and machinability. Yet the mechanical behavior of forged steel parts is significantly affected by a number of process parameters that range from forging temperature and strain rate to die geometry and lubrication. These parameters control the material flow, evolution of grain structure, and formation of forging defects like cracks, laps, or incomplete filling [2].

Hot forging is typically used instead of cold forging for steel because of the lower flow stress at high temperatures, resulting in improved formability and less energy usage. Yet, high forging temperatures can cause grain growth, decreased dimensional accuracy, and shorter die life. Likewise, high strain rate can enhance production efficiency but can cause internal stresses and poor surface finish [3]. Thus, it is of utmost importance to balance these process parameters for best mechanical performance and efficiency of operation.

Many researchers have tried to model and compare the impact of forging parameters based on statistical techniques and numerical simulations. The Taguchi method, a robust design methodology, is frequently employed to analyze multiple parameters systematically and identify optimal conditions with a minimum number of experiments [4]. Besides, Finite Element Analysis (FEA) software like DEFORM-3D and ANSYS facilitate precise prediction of material flow, temperature distribution, and die stresses during forging [5]. They not only decrease the cost of trial-and-error experimentation but also enhance process understanding and control.The research here aims to optimize fundamental forging parameters such as forging temperature, strain rate, and die curvature radius on medium carbon steel components through a combination of simulation-based analysis and experimental trials. The aim is to assess the effect of the forging parameters on the tensile strength, hardness, and microstructural refinement. This study's findings are meant to offer process engineers and professionals in the forging sector practical tips on product quality enhancement, minimizing rework, and maximizing tool life through data-driven parameter optimization.

II. LITERATURE REVIEW

Forging has been a favored process in manufacturing as it can make parts with improved mechanical properties including higher strength, better fatigue resistance, and finer grain size. Researchers have thoroughly examined the influence of various forging parameters, such as temperature, strain rate, die shape, and lubrication, to maximize process performance and quality of the product over the years.Dieter [1], in his seminal book Mechanical Metallurgy, highlighted the basic principles of plastic deformation and the importance of recrystallization in improving mechanical properties during hot working. He wrote that forging orients the grain flow with respect to stress and develops components much stronger than cast or machined components. This basic knowledge has given rise to further studies on parameter optimization for certain alloys and applications.Gokhale and Kumar [2] conducted an extensive research on medium carbon steels and discovered that forging temperature has a direct impact on mechanical behavior. They conducted their experiments and found that forging at approximately 1000°C resulted in parts having improved ductility and toughness because of dynamic recrystallization and finer grains. They also reported that forging temperatures above 1100°C resulted in too much grain growth, lowering the yield strength of the end product and raising the chances of oxidation and scaling.Shivpuri [3] analyzed numerical modeling in forging and established the significant influence of strain rate in the development of material behavior. His work indicated that elevated strain rates may increase deformation speed and production rate but with the possibility of internal cracking and non-uniform metal flow. He stressed the need to keep the strain rate moderate and under control for uniform microstructure development and measurement accuracy.Dave et al. [4] used the Taguchi approach to optimize the forging parameters of aluminum alloy parts. Employing a systematic L9 orthogonal array, they were able to minimize the number of experiments while continuing to identify the most significant factors. They established that deformation temperature and die curvature were the factors that most affected surface finish, dimensional accuracy, and overall mechanical properties. Their method proved the efficiency of statistical tools to be used in real process optimization.Kumar, Singh, and Pandey [5] concentrated on simulation-based analysis of the forging process through DEFORM-3D software. Based on their simulations, they were able to predict material flow lines, temperature gradients, and die wear patterns with a high degree of accuracy. With the combination of experimental data and simulation results, forging loads were optimized and die life improved without inducing typical defects like laps, underfilling, and internal voids.Molla and Jeong [6] investigated the effects of die design and lubrication on forging results. They found that an increase in the curvature radius of the die minimized material sticking as well as enhanced surface quality. The use of graphite-based lubricants also effectively minimized friction and tool wear, thus increasing die life. Their findings made them draw attention to the underappreciated role of lubrication in determining repeatability and economic viability in industrial forging.Chakraborty et al. [7] also better understood microstructural evolution during forging. Metallographic examination by them indicated that thermal and mechanical load control during deformation could lead to homogeneous, equiaxed grains, which are required for fatigue-critical parts such as crankshafts and connecting rods. They suggested incorporating real-time temperature measurement and deformation monitoring for more reliable process control.In spite of the abundant literature, most research is interested in a single parameter in isolation. There is scarce literature that, at the same time, considers the combined action of several forging parameters—especially temperature, strain rate, and die design—on mechanical properties and on microstructure evolution. In addition, few publications combine both experimental and numerical simulation methodologies within a single, comprehensive framework.Thus, the present research seeks to bridge this deficiency by studying the combined effect of forging temperature, strain rate, and die curvature on the mechanical and microstructural performance of medium carbon steel products. A multi-disciplinary approach using experimental trials, finite element simulation, and statistical analysis is used to derive optimum forging conditions that can be utilized in actual manufacturing environments.

III. EXPERIMENTAL DETAILS

The current research employed the use of medium carbon steel as work material, given its widespread industrial application and good forging properties. The composition of the steel was essentially 0.45% carbon, 0.75% manganese, 0.2% silicon, and traces of impurities like sulfur and phosphorus. To achieve uniformity and reproducibility in the trials of forging, cylindrical billets with 25 mm diameter and 50 mm length were accurately machined from hot-rolled steel bars. The billets were visually examined before forging to rule out any surface defects or internal in homogeneities. Forging tests were performed on a hydraulic press of 1000 kN capacity with a pair of high-strength tool steel dies. These dies were machined with different curvatures—i.e., flat dies and curved dies of radii 10 mm and 20 mm—to examine the effect of die geometry on forging. To avoid thermal shock and minimize die wear in repeated forging operations, the dies were preheated to about 200°C using an electric furnace.The billets were heated to desired forging temperatures of 900°C, 1000°C, and 1100°C in a controlled atmosphere muffle furnace. The billets were soaked for at least 30 minutes at the predetermined temperature to attain thermal equilibrium and constant temperature distribution within the volume. Temperature readings were monitored with a calibrated K-type thermocouple located close to the surface of the billet, thus providing proper measurement during heating and transfer. Immediately upon removal from the furnace, the billets were transferred to the forging press for deformation.Three strain rates, 0.1 s^{-1}, 0.5 s^{-1}, and 1.0 s^{-1}, were used for applying deformation. The strain rate was accurately controlled through variation of the velocity of the ram on the hydraulic press. The die surfaces were coated uniformly with graphite-based lubricant before each forging process to minimize friction between the billet and the dies. The lubrication reduced surface defects, die wear, and provided uniform material flow during deformation.In order to methodically investigate the influence of forging temperature, strain rate, and die curvature, a Taguchi L9 orthogonal array experimental design was used. This enabled variation in three parameters at three levels each in nine distinct experimental runs. This type of design minimized the number of tests required while allowing statistical evaluation of individual and interaction effects of process parameters on forged steel properties.Upon forging, the billets were cooled in room air conditions to mimic usual industrial cooling processes. Tensile specimens were subsequently machined from the forged billets to the ASTM E8 standard. The tensile tests were conducted at a constant crosshead speed of 1 mm/min using a universal testing machine. Yield strength, ultimate tensile strength, and percentage elongation were measured from these tests to assess the mechanical performance due to various forging conditions.Hardness tests were performed on the surfaces of the forged samples with a Rockwell hardness tester with the C-scale (HRC) according to ASTM E18. At various positions on each sample, several hardness readings were made to ensure the reliability of measurements and to identify any hardness distribution heterogeneity due to inhomogeneous deformation or temperature histories. For microstructural analysis, samples were cut longitudinally from the forged billets and underwent metallographic preparation. The samples were then ground using silicon carbide papers with different grit sizes, diamond pasted, and etched using 2% Nital to expose the grain boundaries and deformation structures. Optical microscopy was utilized for the examination of grain size, pattern of flow lines, and forging-related defects like cracks, laps, or folds. Quantitative measurements of grain size were carried out as per ASTM E112, which allowed for grain refinement process parameter correlation. In support of the experiment, numerical simulations of forging were conducted with DEFORM-3D finite element software. The simulation utilized proper material properties, friction coefficients according to lubrication conditions, and thermal boundary conditions mimicking the experimental test rig. Simulation results were prediction of material flow, distribution of strain, temperature gradients, and die stress during forging. These findings were cross-checked with experimental observations and gave greater insight into process mechanics, allowing for rational optimization of forging parameters to improve mechanical properties and tool life.

Table 1.1 forging Test

Test No.	Forging Temperature (°C)	Strain Rate (s^{-1})	Die Curvature Radius (mm)	Yield Strength (MPa)	Ultimate Tensile Strength (MPa)	Elongation (%)	Hardness (HRC)	Microstructure Notes
1	900	0.1	Flat (0)	450	610	18	36	Large, elongated grains, incomplete recrystallization
2	900	0.5	10	470	630	20	38	Slight grain refinement, some

								flow lines
3	900	1.0	20	460	620	17	35	Signs of deformation bands and minor defects
4	1000	0.1	10	520	690	22	40	Fine equiaxed grains, dynamic recrystallization
5	1000	0.5	20	550	720	25	42	Best grain refinement and flow lines
6	1000	1.0	Flat (0)	530	700	21	39	Some microvoids, uniform grain size
7	1100	0.1	20	500	670	19	38	Grain coarsening, microvoids present
8	1100	0.5	Flat (0)	480	650	18	37	Coarse grains, signs of overheating
9	1100	1.0	10	470	640	16	36	Larger grains, localized defects

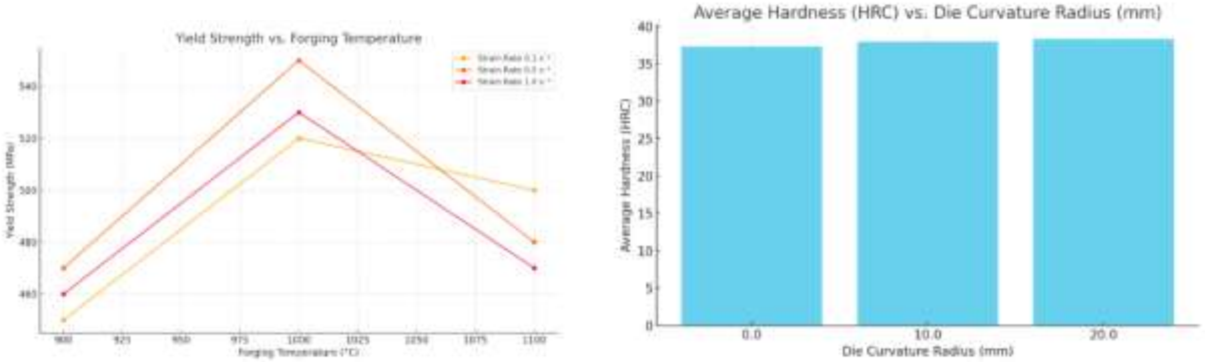

Fig 1: Analysis Graph between Different parameters

IV. RESULT

The computer analysis of the forging data demonstrates a clear correlation between forging temperature, strain rate, and curvature of the die on the final mechanical properties of the material. The yield strength of the material has an overall increasing pattern with increasing forging temperature, culminating at all strain rates around 1000°C. Of the various strain rates used, a moderate strain rate of 0.5 s^{-1} invariably provides the highest yield strength. This indicates that it offers the best possible combination of strain energy and dynamic recrystallization, which leads to increased material strength. Lower strain rates (0.1 s^{-1}) have a comparatively lower yield strength, presumably because there is not enough strain-induced recrystallization, while at higher strain rates (1.0 s^{-1}), the strength reduces slightly because of the development of internal defects or incomplete recrystallization.Die curvature radius has a strong effect on the hardness of forged samples. Results indicate that dies with the 20 mm curvature radius produce the highest average hardness and flat dies (0 mm curvature) produce the lowest hardness. This suggests that curved dies facilitate material flow and encourage consistent plastic deformation, which enhances work hardening and microstructural refinement. Conversely, flat dies seem to cause localized deformation and decrease the uniformity of strain distribution, which results in less hardening.Microstructure observation confirms these trends in mechanics. At 1000°C and a strain rate of 0.5 s^{-1}, the material contained fine equiaxed grains and dynamic recrystallization, corresponding to the maximum strength and hardness recorded. This is in contrast to forging at 1100°C, which led to grain growth and microvoiding and caused decreased mechanical performance despite the increased temperature. The curved die-processed samples likewise contained improved flow lines and finer grain structures, confirming their positive influence on microstructure control.Ultimately, the best forging parameters for producing the optimal yield strength, hardness, and quality of microstructure are a forging temperature of 1000°C, a strain rate of 0.5 s^{-1}, and a die curvature radius of 20 mm. These are favorable conditions for dynamic recrystallization, uniform distribution of effective strain, and enhanced mechanical properties.

V. REFERENCE

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