Recent Advancements in Forging: A Computing Overview

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Abstract: *The defects in the forged objects are raises by uncontrolled grain deformation and causes the varying material strength at the different section. To provide the control on these detrimental effects standard grain deformation with control on unidirectional material properties must be used. It discards the residual stresses and thereby the failure of forged objects. The current research is to review and interpret controlling parameters of grain deformation in forged components to improve the material strength. The study is concentrated on grain slip, work hardening, material fibre, stress analysis of grain fibre, die selection approach for deformation, microstructure analysis, mathematical modelling for material deformation and establishing the hierarchical relationship between process parameters. The study incorporates key finding of the published research, that includes the theoretical, experimental, software simulation study. The study states that the governing equation of the forging process can be derived to provide the optimum selection of process parameters. The standard formulation of the methodology for the forging process design can commit the highest performance results of the forged component.*

Keywords: Forging design; Process Parameters; forged-microstructure study; forging governing equation.

1. Introduction

The advancement in the field of forging is done promisingly and its adoption is also evident in industries. The forged components impart significantly higher strength over the other manufacturing process such as casting or machining. The forged component offers the higher material strength due to work hardening at the plastic state of [29]. The cold working of forged components prevents the recrystallization of grains and maintains the material properties developed in the deformation state [14]. Although the cold worked forged product thus offers the best mechanical strength in operation still the grain flow control in actual operation is very difficult due to plastic state deformation. The uncontrolled grain flow caused the disturbance in grain fibre lines and can be witnessed under microscopic visualization [20]. To eliminate this ill effect of uncontrolled grain flow it is necessary to study and optimize the critical parameters in operation. The forging process has critical parameters defines the system performance are τ- Shear stress, m- Friction coefficient (Constant friction model), σ - Yield stress, F- Forging Force, R - Tool radius, δ - Reduction rate, μ - Friction coefficient (General friction model Model), L - Length in the chamber [32]. The hierarchical relationship among these parameters is given in figure 1.

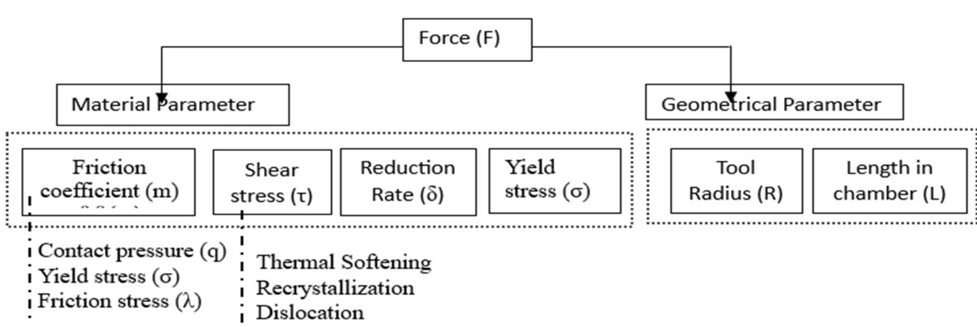

Figure 1. Forging process parameters

2. Forging process parameters

The selection of the process parameter for the design of forging process is dependent on the various operational and material properties parameters. The individual parameter based on the process study and operation is evaluated and results are interpreted from the research published around the globe. The selection of the basic parameter based on process requirement are discussed in this research. The mathematical formulation for the individual process parameter or the technological approach for the selection of these parameters are discussed in the current research.

2.1 Material Parameter

In forging process, the material undergoes frequent deformation in each stroke of forging operation. The effectives of the forging process are mainly dependent on the analysis of the accurate material parameter for design of forging process. The critical study on the selection of these material parameter provided as under,

2.1.1 Friction Coefficient (m, *f*)

Friction plays an important role in forging operation. The friction in forging process is dependent on Contact pressure (q), Equivalent yield stress (σ) & Normalized friction stress (λ) [21]. In forging the two elastic molecules are stressed beyond the plastic stage and the regardless of the smoothness of the molecules the surfaces are in contact with each other. The surface contact as well as the high stress asperities, are responsible for micro-weld on the overlapping molecules. The friction model at the deformation section is shown below,

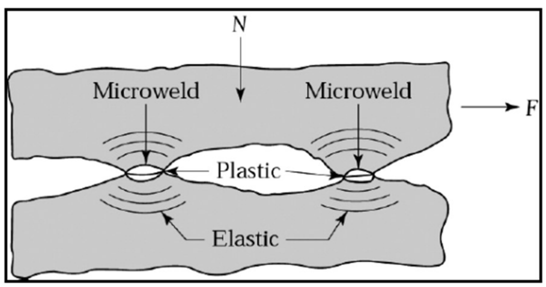

Figure 2. Friction model at the forging section

The analysis of the friction in the forging is evidenced since 1943. The constant friction model is applied for the grain friction in earlier stages. The friction model is applicable for the homogeneous material body [6]. The friction model considers that the friction stress is proportional to the interface pressure. The friction model is given by

$$\tau = m\,k \quad (1)$$

τ - Frictional Stress, m - Friction factor, k - Shear flow stress. The friction law can be applied only when the punch pressure is not higher than the yield stress of material.

The general friction model is developed to overcome the limitations of constant friction model. The model works on the basic functional relationship between frictional stress and normal pressure, surface topography, compressibility of the lubricant and length of sliding, viscosity [25]. The friction model developed is based on the slip-line theory of analysis and is given as,

$$\tau = f\,k\,\alpha \quad (2)$$

$\tau = f\,k\,\alpha$; τ - Friction Stress, f - Friction factor ($0 \le f \le 1$), α - Ratio of real contact to the apparent contact area, k - Shear flow stress (Yield stress in pure shear). The friction model suits well for the pressure of $q/\sigma_b = 1.3$.

Both the model constant friction and general friction works on the same theory of proportional relationship between frictional shear stress, normal stress, and yield shear strength [7][10]. The constant friction model is denoted as 'm' and general friction model as 'f'. The research advancement in the frictional analysis of forging combines both the frictional model. The research provides the approximate relationship between m and f. Based on analysis and experimental investigation the proportionate relationship is found as $m = 2$. The exact true relationship between m and f *is* estimated and gives the proportionate relationship as [26]

$$f = m^{0.9}/2.72(1-m)^{0.9} \tag{3}$$

The model is validated with the experimental analysis on samples and got the accuracy of 14 % in true load trials.

The contact pressure at the deformation layer (x) is

$$P = 2\,k\left\{1 + \frac{m(w-x)}{h}\right\} \tag{4}$$

Where w and h are width and height of object [4]. The frictional shear stress is a combined result of the material parameters like equivalent stress(σ_{eq}), normal stress (σ_N), the sliding velocity (v_{rel}), the flow stress (σ_y), and the shear yield strength k of the work-piece material. The mathematical formulation of the frictional shear is given as

$$\tau_r = m\left[\left(1 - \frac{\sigma_{eq}}{\sigma_y}\right)\sigma_N + K\,.\frac{\sigma_{eq}}{\sigma_y}\left(1 - \exp\frac{-|\sigma_N|}{\sigma_Y}\right)\right].f\,v_{rel}. \tag{5}$$

Here $f\,v_{rel}$ is a function of constant parameter C having the value in the range of 1 to 150 and is dependant function of sliding speed and the frictional shear stress. The factor is given as

$$f\,v_{rel} = -\exp\frac{-1}{2}\left(\frac{v_{rel}}{C}\right)^2 \tag{6}$$

2.1.2 Shear stress (τ)

In forging the molecule shear plates are get generates because of the concentration of deformation at the narrow zone. The shear plates are due result of the of the material deformation which is analysed in three models [11]. In the primary stage of material deformation, the deformation model is considered as a thermal softening model. In this model due to excessive pressure the temperature at the localized area is reaches to maximum value. The maximum temperature at the localized area causes the plastic state of material and the grain strain localization is achieved. The second deformation model is the model of material recrystallization. In this model the strained grains release the stored dynamic energy. The release of energy caused the grain recrystallization. The newly formed grains are deformed to lesser size and offers the softening of the shear zone at nano scale [24] [27]. The third model is grain dislocation and shear plate formation. The dislocated grains get accumulated at the immediate obstacle shear plate and thus causes the large strain at the localized area.

To perform the mathematical formulation, the experimental study is performed on standard specimen and the stress flow pattern of the deformed material is studied. In actual loading the X shaped deformation pattern is followed by the part. The x orientation states that the shear band adjusts themselves at the fixed angle with respect to the deformation axis. The shear bands are actually inclined at 45^0 with respect to the deformation axis. The stress gradient transfers uniformly across the deformation window. The standard X deformation orientation is as shown in figure 2 [3],

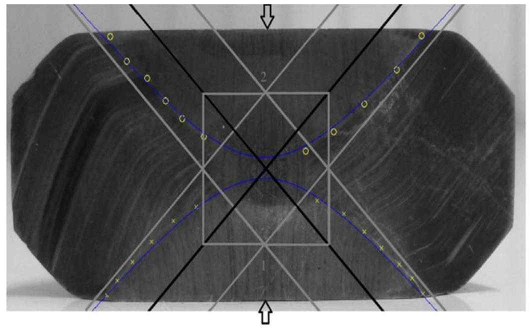

Figure 3. X shaped shear deformation model

From the microstructure analysis it has been seen that the impact force in forging creates the plane stress wave and extends towards longitudinal axis. Also, the stress wave at the lateral plane reflected back totally due to elemental mismatch. The reflected wave causes the concentration of stress at the localized area. The stress concentration is split into two segments i.e. along the 45^0 orientation plane and other along the lateral plane. The segments will have the same intensity of stress whereas the element in each section will have the same magnitude. The micromechanical analysis of the stress pattern needs to be done to perform the mathematical formulation. To have the computing overview of the shear stress the pure plane stress theory can be applied.

The deformation is takes place in two stages i.e. deformation below recrystallization temperature and deformation above recrystallization temperature. The shear stress in the two phases is evaluated by 'Tresca' shear stress model [8]. The model considers the deformation as strain hardening phase and strain flow rate (recrystallization phase). The strain hardening shear flow rate is given by

$$2\,\tau_{flow} = K\,\varepsilon^{n} \qquad (7)$$

The Bulk modulus (K) and n are the material property and constant. The shear stress in the recrystallization phase is given as by

$$2\,\tau_{flow} = C\,(\dot{\varepsilon})^{\,m} \qquad (8)$$

The Modulus of rigidity(C) and m are the material constant. The strain rate $\dot{\varepsilon}$ is given as

$$\dot{\varepsilon} = {}^{v}/_{h} \qquad (9)$$

Where v is platen velocity and h are instantaneous height. The platen velocity is considered as to be a function of normal operating speed of the forging die. The operating speed of die at which it strikes on the work-piece is 750 feet/min.

2.1.3 Reduction Rate (δ)

The Reduction ratio or the deformation rate are usually a dependant function of change of cross section at the elongation point. For the selection of the reduction rate there is need to overlook for the parameters like sudden variation in cross section, relative length of stroke, material deformation rate, type of edging, friction, operating temperature, and the shape of dies. The quality of the forged components is not only affected by the metallurgical parameters but also the technological parameters. In forging of the complicated shape, the optimum selection of these technological parameters is most important to produce the uniform strength on the developed forged component [5]. The optimum selection of the technological parameters is done based on the operational experience. The mathematical expressions available for the technological parameters are based on empirical experience in forging shops. The empirical relations provided must be studied to trace the true relation among them.The reduction ratio is mostly estimated by the change of cross section. The basic equations used for reduction rate is

$$K = {}^{1}/_{(1 - \mathcal{E}_h (1 - f))} \tag{10}$$

Here $\mathcal{E}_h$ is rate of deformation, f is the coefficient of spreading at elongation [13]. The coefficient of spreading is a function of relative width stroke l_z/b_i. Here l_z is width of applied force and b_i is the total width of the forged component. The coefficient of forging is dependent on relative stroke of forging and can be selected from the standard table available in literature. The reduction rate is significantly affected by the relative length of stroke i.e. l_z/h. Where h is dropping height.

An experimental investigation is done on different steel plate for varied compositions by Takeshi [28]. The experimentation is done for the reduction ratio of 4, 6, 7, 8, 12 and 20. The experimental result shows that mechanical properties in the direction of forging is improved significantly upto reduction ratio of 12.5. The grain elongation, reduction of area and the notch toughness is improved rapidly. In the same experimentation result shows that the mechanical properties provide the best results when the reduction ratio is maintained till 8. The research states that the longitudinal tool direction and material moment facilitate the reduction ratio tobe maintained till 12.5. Whereas for lateral material moment the reduction ratio should be maintained till 7 to 8.

The reduction rate in forging is sometimes also defined in terms of the hydraulic press capacity. The volumetric deformation based on the material constant is estimated and the successive volumetric reduction is achieved [9]. The unit reduction in single draft is given as,

$$\mathcal{E}_h = \nabla_h / h_o \tag{11}$$

Here $\mathcal{E}_h$ for hydraulic press is 0.2 to 0.3. Also, ∇_h and h_o are deformation height and total billet hight. The research is also done on the steel material to estimate the effect of reduction ratio on the tensile strength and % elongation [1]. The result shows that at the lower reduction ratio i.e. in the range of 1 to 5, the material strength is improved considerably. Whereas with further increase in reduction ratio the material strength is reduced significantly. The % elongation is improved considerably for the reduction ratio of 5 to 10, with further increase in reduction ratio the % elongation is reduced partially.

The experimental research is done on the steel plates to identify the relation between the tool size and the deforming surface area [16]. The elastic-plastic state computer analysis is done for the varied material passes. The deformation is mentioned in terms of the strain induced in three-dimensional analysis. The analysis shows that the forging reduction in lengthwise pass provides the best result for the maintained surface contact ratio of 0.7.

2.1.4 Yield stress (σ)

In forging process, the material is stressed beyond the plastic stage, wherein, there is no straight correlation between the stress and strain. The plastic state deformation is highly impacted by applied load and the way of application. The forging process is carried out with a viewpoint of design where the material should deform, such that, the material strength is restored without any excessive yielding. In the plastic deformation stage, the material gets destroyed abruptly due to which it is very difficult to express the deformation in terms of load [17]. For design formulation, the correlation is performed with some assumptions in failure analysis.

In plastic stage deformation the material gets strain hardened due to which the stress at the plastic deformation is of higher magnitude. The yield stress at the plastic deformation zone is given as power expression

$$\sigma = K\,\mathcal{E}^n \qquad (12)$$

Here n is strain hardening coefficient and the value can be traced from slope of log plot of stress strain curve for different material. The research has shown there is high correlation between the strain rate and the plastic deformation of the material. At the moderate strain rate in the range of 10^{-3} s^{-1} to 10^{-1} s^{-1}, the yield strength of the material dose not changes. Whereas with further increase in the strain rate the 1 s^{-1}, the yield strength improved slightly and reaches to highest yields strength when the strain rate reaches to 10 s^{-1} [31].

The yield stress in forging is estimated in relation to the Young's modulus (E) and 0.2 % offset rule [2]. The Young's modulus is the estimated value of stress strain within the proportionality limit and is given as

$$\sigma = E \times \epsilon \qquad (13)$$

The 0.2 % offset method is the most widely used method for estimation of Yield stress. The method is adopted considering the yield strain as 0.2 % fraction of Young's modulus then the Yield stress for the section is given as $\sigma = 0.002 \times E$.

The experimental investigation is done on the steel having different volume fraction of martensite [12]. The intercritical temperature heating is provided to create the true effect of forging operation. With the decrease in volume fraction 0.18 to 0.2 the minimum of the yield strength of material is observed. For the consideration in design of process the Yield stress to Tensile stress ratio is considered to be 0.45.

2.2 Geometrical parameter

The size and orientation of the forged product guides for the selection of deformation rate. The forging design is highly affected by the forging radius, tool size and the length of travel in chamber. In forging design, the selection of geometrical parameter is referred in terms of grade of material. The deformation is varied as per the type of material still the research finding for the selection of geometrical parameters are provided in the discussion.

2.2.1 Tool Radius (R)

The selection of Tool Radius and the deformation rate plays an important role for the effectiveness of the forging operation. The selection of tool radius and tool profile affect the accuracy of forged product. The improper selection of tool profile and tool radius makes it impossible for the work-piece to get deform as the surface under deformation attain the concave profile and the forging force gets directed toward the centripetal direction [18]. The mathematical modelling for the deformation at the punch of forging die is done and the deformation results are validated experimentally. The stress material flow tobe maintained in the defamation plane and the tool radius tobe maintained is given as

$$\sigma_z = \left[1 - \frac{2\,m}{\sqrt[3]{3}}\right]\left(\frac{a}{h}\right)\left(\frac{r}{a} - 1\right)\sigma_f \qquad (14)$$

Here the σ_z is the shear stress tobe maintained in Z direction, m - friction coefficient, a deformation area under stress, r – tool radius. For the smooth deformation and better material properties r > 4a.

An experimental investigation is done for different length to diameter (L/D) ratios and different and varying die speed [15]. With the reduction in operating height the radial and axial strain rates increase exponentially. For the 45 % of the height reduction the die speed needs to raise by 0.01 m/s. The higher strain rate offers better deformation and maintains high density at the lower operating height and higher operating speed. The experimentation is also done for filling up the die with the billet for close de forging process [30]. The experimentation is done with the different idented specimen. The forging load and slush generated for the forging process is evaluated for different aspect ratio (H_0 / D_0) on cylindrical objects. For the aspect ratio of 1.4 and 1.6 the shush generation is 10 % and 15 % respectively. The experimentation estimated the tool radius in the form of indentation ratio as

$$IR = \ln {}^{H_0}/_{H}. \quad (15)$$

H_0 volume reduction in single stroke and H is total billet height.

The mathematical modelling and the experimental validation of cold forging process is done for varied material composition [22]. The appropriate tool radius (die land geometrical parameter) ensures the uniform distribution of the material flow and thereby reduces the residual stresses in forged components. Research has been done to determine the relation between the tool radius (die land parameter) and the forging force required for design. The forging force required for the deformation is given as

$$F = 2\,K_F\left[4\,\mu\left(\frac{H}{D} + \frac{h}{d}\right) + \left(\frac{\mu}{\sin\acute{\alpha}} + 1\right).\ \ln\frac{D^2}{d^2}\right] \quad (16)$$

Here μ - coefficient of friction, D - Billet diameter (mm); d - Tool radius (die land diameter mm), h - Die land height (mm), a - die half angle (◦), H -billet height (mm) and k_f- maximum tangential stress (N/mm^2). The derived equation is validated by performing the correlation analysis with Finite Element Analysis results and experimental forging load estimation. The maximum variation in the results was about 8.5 %.

The advancement in the Finite Element methods applied to forging process are developed so promisingly by which the accurate and robust process operation and uncertainties can be evaluated. The finite element simulation gives the visualization of flow lines, die forces, velocities, and final configuration of product. The Finite Element method is mostly concerned with the identification of punch force. The backword extrusion process of forging is investigated for the punch diameter, punch face, flow angle and land height [23]. The force equation in terms of the geometrical parameters of the geometrical parameters of the punch are given as,

$$f = b_0 + b_1 z + b_2 r + b_3 a + b_4 h + b_5 z^2 + b_6 r^2 + b_7 a^2 + b_8 h^2 + b_9 z.r + b_{10}.z.a + b_{11} z.h + b_{12}.r\,.a + b_{13}.r.h + b_{14}.a\,.h \quad (17)$$

Here *f* – Force, $b_1, b_2, b_3 -- b_{14}$ – Regression Coefficient, z, r, a, h, L_0/D_0 – Billet size ratio, $\frac{(A_0 - A_1)}{A_0}$ - reduction ratio. The proposed Finite Element model gives 95 % of the confidence level for the experimental test data.

2.2.2 Length in chamber (l)

Imparting structural deformation in the forging is dependent on grade of material, internal imperfections, intensity of structural changes. The lengthening in forging operation is estimated based on the change in forging cross section and material grade available. The analysis is done on the effect on deformation by relative length of bite to trace the effect on closing imperfection in forging. The study on deformation in the forging operation guides for the selection of 27 % of the spreading and 73 % of lengthening length in operation. The spreading coefficient is also a major parameter which affect the selection of length in chamber [20]. The relation between the material grade and the spreading coefficient is given as

$$K = {}^{1}\!/_{1-\ \varepsilon\,(1-\ f)} \tag{18}$$

Here ε - relative deformation and K is material modulus. The spreading coefficient is a function of die friction parameter and the sectional deformation. The spreading coefficient is given as $f = \varphi\left(\frac{l_z}{b_0}\right)$. Here φ – Friction coefficient l_z & b_0 deformation length and width respectively.

3. Summary and Conclusion

The forging is a complex process in which the overall performance is dependent on various morphological, rheological properties and process parameters. To understand the effect of individual parameter involved in the process micromechanical study of the process is needed. The approach of study for the material deformation differs from material to material as chemical composition and the material failure mode gets varied with the change in material composition. Although all the limitations in study the statistical hierarchy within the same material group is organized by deformation mode and the research findings are provided. The work discusses the critical parameters needed to consider for the design of forging process. Till date there is no such a standard design formulation is available for the design of forging process. The need of standard design process formulation can be addressed by the research finding provided in the present research. The current research summarized the experimental and analytical finding of the process parameters. The present research group the process output parameter as forging force whereas the input parameter is grouped as material parameter and the geometrical parameter. The research interpretation findings are provided as under,

1. The constant friction model and the general friction model are used for friction analysis in forging. The selection of friction model is based on the forging pressure.
2. The shear deformation in forging follows X shape material flow pattern. The 'Tresa' model is used for analysis of shear deformation in which the shear stress analysis covers the deformation as strain hardening phase and strain flow rate.
3. The selection of reduction rate is dependant function of coefficient of spreading. The spreading coefficient is selected from the standard graph available in research reports. The longitudinal material moment offers the reduction ratio tobe maintained from 8 to 12.5 whereas for lateral moment the reduction ratio should be maintained from 7 to 8.
4. The estimation of yield stress is done based on 0.2 % offset rule. Whereas some material module offers the yield stress tobe considered as a fraction of tensile stress.
5. The tool radius is selected based on concave material deformation pattern under the tool land. The standard mathematical model and the FEA model are used to select the tool radius.
6. The length in chamber or deformation length is dependent on spreading coefficient and the grade of material. The standard mathematical model is available for lengthening in chamber. Whereas the standard deformation proportion for the spreading and lengthening are 27 % and 73 % respectively.

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