The Simulation and Analysis of the Closed Die Hot Forging Process by A Computer Simulation Method

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ABSTRACT

The objective of this research work is to study the variation of various parameters such as stress, strain, temperature, force, etc. during the closed die hot forging process. A computer simulation modeling approach has been adopted to transform the theoretical aspects in to a computer algorithm which would be used to simulate and analyze the closed die hot forging process. For the purpose of process study, the entire deformation process has been divided in to finite number of steps appropriately and then the output values have been computed at each deformation step. The results of simulation have been graphically represented and suitable corrective measures are also recommended, if the simulation results do not agree with the theoretical values. This computer simulation approach would significantly improve the productivity and reduce the energy consumption of the overall process for the components which are manufactured by the closed die forging process and contribute towards the efforts in reducing the global warming.

Keywords: Closed die hot forging, H/D ratio, Modeling, Simulation.

1. INTRODUCTION

In the highly competitive present era, the mass production requirements in the engineering industries have increased the demand for the forged components. Forging process, usually involve multiple preforming processes followed by a specified finishing process.

Process simulation has become an increasingly important tool for the development of new process or improvements in the existing process. The effective use of simulation tools will not only reduced the cost and the time necessary for the development of new products significantly but also helps and contributes in efforts of lowering the energy consumption of the processes and thereby contributes towards the efforts of reducing the global warming effects. The process requires a lot of experience and skill to optimize the quality, costs and lead time.

The objective of this research work is to simulate and analyze the closed die forging process. The main focus is to know the variation of stress, strain, force, temperature, etc. at different stages of forging of AISI 1016 by a computer simulation method. In this approach, the closed die forging process has been divided in to two stages i.e. deformation process before flash formation and after flash formation.

The designs based on results of simulation are required to be evaluated to make sure that the material would flow as per the requirement in the die cavity.

2. MODELING OF CLOSED DIE FORGING

The modeling and simulation of closed die forging process has been carried out by using analytical and numerical methods [1], [12]. For the purpose of simulation, a cylindrical shape billet, having appropriate H/D ratio, have been deformed between two die halves as shown in Fig. 1. The deformation process before flash formation and after flash formation has been depicted in Fig. 2 and Fig. 3 respectively.

Estimation of the Flow Stress

Forging is a deformation process which involves several variables interconnected by more or less complex functions. The method discussed here is used to simulate the hot die forging process to determine the flow stress, maximum stress, strain before flash formation, strain in flash, load, temperatures of die and billet. The flow stress relationship has been implemented as a subroutine [1].

$$\sigma_f = C\dot{\varepsilon}^m \tag{1}$$

Where, $C = f(\varepsilon, T)$

The parameters C and m are available in the material property hand books for different billet materials used in various types of forming processes.

Calculation of Strain

The strain in the work material inside the die cavity as well as in the flash during different stages have been calculated as follows [4].

The strain before flash formation, as shown in Fig. 2, could be computed as,

$$\varepsilon = \ln(H / h) \tag{2}$$

During flash formation, as depicted in Fig. 3, the strain in flash, indicated as encircled digit 1 (zone 1), may be calculated as,

$$\varepsilon_1 = \varepsilon_{tc} + \ln(\bar{t}_c / \bar{t}) \tag{3}$$

At the end of the process, the material is assumed to flow in to flash by shearing along the surface indicated by dashed line in Fig. 3. Therefore, the strain in zone 2, shown as encircled digit 2 (zone 2) i.e. ε_2 is equal to ε_{tc} which is the zone between the shearing line and the die, and the strain in zone 3, represented by encircled digit 3, is ε_3 may be computed as,

$$\varepsilon_3 = \varepsilon_{tc} + \ln(\bar{h}_c / \bar{h}) \tag{4}$$

$$\bar{h} = 0.8\bar{t}(L / 2\bar{t})^{0.92} \tag{5}$$

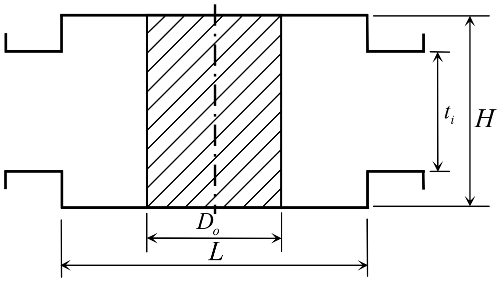


Fig. 1 Billet and Die geometry: Initial configuration

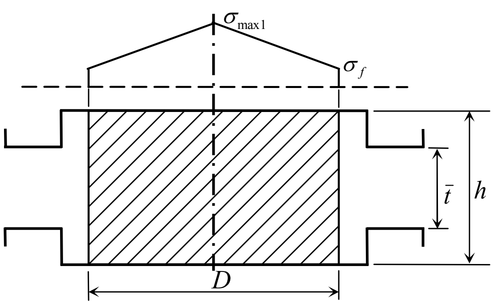


Fig. 2 Billet and Die geometry: Upsetting

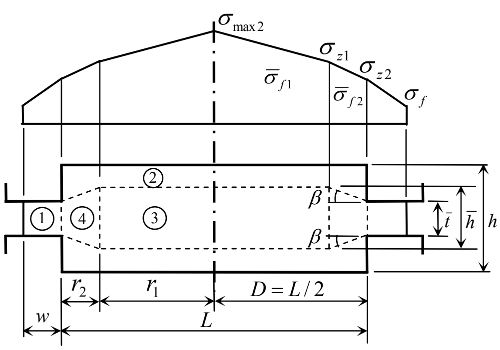


Fig. 3 Billet and Die geometry: with Flash

The mean height of the convergence region 4, indicated by encircled digit 4, in Fig. 3, could be calculated as,

$$\bar{h}_1 = (\bar{h} + \bar{t})/2 \tag{6}$$

The strain in the convergence region 4 may be obtained as,

$$\varepsilon_4 = \varepsilon_{tc} + \ln(\bar{h}_c / \bar{h}_1) \tag{7}$$

Calculation of Strain Rates

The strain rates for the various stages of closed die forging process may be calculated as follows:

Deformation process before flash formation as shown in Fig. 2 may be computed as,

$$\dot{\varepsilon} = v / h \tag{8}$$

Deformation process after flash formation as depicted in Fig. 3 may be calculated as,

$$\dot{\varepsilon}_1 = v / \bar{t} \tag{9}$$

$$\dot{\varepsilon}_3 = v / \bar{h} \tag{10}$$

$$\dot{\varepsilon}_4 = v / \bar{h}_1 \tag{11}$$

Calculation of Stresses

The stress before flash formation as shown in Fig. 2 may be computed as,

$$\sigma_{\max} = \sigma_f (1 + (\mu_1 D / h)) \tag{12}$$

The stresses after flash formation as represented in Fig. 3 could be calculated as,

$$\sigma_{z2} = 2\mu_1 \sigma_f (w / \bar{t}) + \sigma_f) \tag{13}$$

$$\sigma_{z1} = (K_2 / K_1) \ln(\bar{t} / K_3 + K_2 r_2)) + \sigma_{z2} \tag{14}$$

$$\sigma_{\max} = ((2\mu \sigma_{f1} r_1) / h) + \sigma_{z1} \tag{15}$$

Where,

$$K_1 = -2 \tan \beta \tag{16}$$

$$K_2 = -\sigma_{f2} K_1 + 2\mu_2 \sigma_{f2} (1 + \tan^2 \beta) \tag{17}$$

$$K_3 = \bar{h} - r_2 K_1 \tag{18}$$

$$\tan \beta = [1 - \{((\bar{h}/\bar{t}) - 1)/((\bar{h}/\bar{t}) \ln(\bar{h}/\bar{t}))\}]^{1/2} \tag{19}$$

Calculation of Forces

The force required for deformation process before flash formation for the geometry as shown in Fig. 2 could be,

$$F = 2\pi \sigma_f [(h^2 / 4\mu_1^2)(\exp(D/h) - 1) - hD / 4\mu_1)] \tag{20}$$

The force required for deformation process after flash formation for the geometry as shown in Fig. 3 would be,

$$F = F_1 + F_2 \tag{21}$$

Where,

$$F_1 = 2\pi \sigma_{z1} [(\bar{h}^2 / 4\mu_2^2)(\exp(\mu_2 L / \bar{h}) - 1) - \bar{h} L / 4\mu_2)] \tag{22}$$

$$F_2 = \sigma_f (\pi / 4)(2Lw + w^2)(1 + (\mu_1 w / 3\bar{t})) \tag{23}$$

F_1 is the average force on the billet and F_2 is the average force on the flash land.

Calculation of Die and Billet Temperatures

The temperatures during the process are calculated separately within the die cavity and in the flash [2], [14].

Die cavity

The analysis for the temperature distribution for a system comprising of die-lubricant-billet may be summarized in non-dimensional form as follows.

The time has been transformed in to a non-dimensional parameter N_θ as follows.

$$N_\theta = \alpha \theta / H^2 \tag{24}$$

$$\alpha = \lambda / \rho C_P \tag{25}$$

$$FS_{Die} = (T_D - T_{DO}) / (T_{BO} - T_{DO}) \tag{26}$$

$$FS_{Billet} = (T_{BO} - T_B) / (T_{BO} - T_{DO}) \tag{27}$$

The FS_{Die} and FS_{Billet} are the two non-dimensional functions representing the change in temperature at different locations within the die and the billet.

For different H/D ratio, the non-dimensional parameter N_θ is related with FS_{Die} and FS_{Billet} as shown in Fig. 4 and 5 respectively.

The change in temperature with time could be calculated as follows.

$$T_D = T_{DO} + FS_{Die}(T_{BO} - T_{DO}) \tag{28}$$

$$T_B = T_{BO} - FS_{Billet}(T_{BO} - T_{DO}) \tag{29}$$

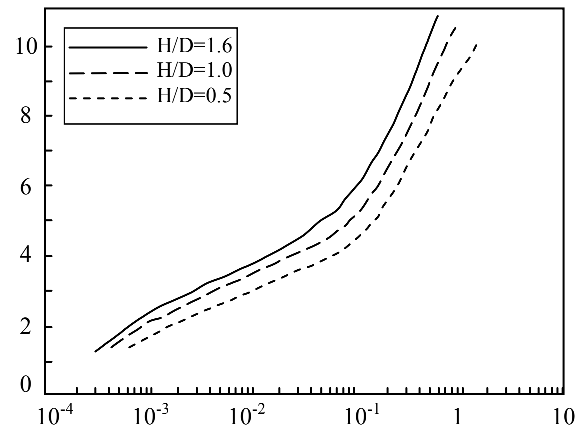


Fig. 4 FS_{Billet} Vs. N_θ

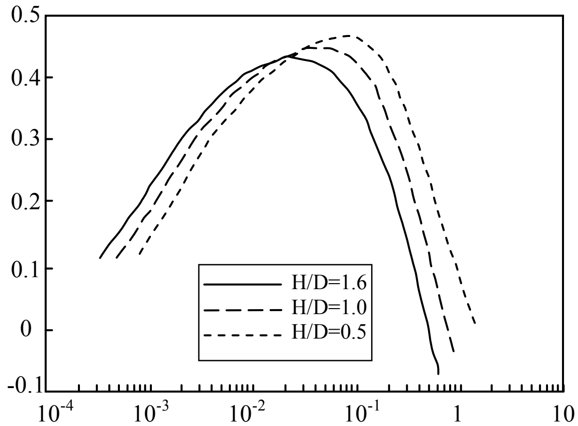


Fig. 5 FS_{Die} Vs. N_θ

The temperature rise due deformation may be computed as,

$$\Delta T = \int (\sigma_f / \rho\, C_p)\, d\varepsilon \tag{30}$$

The heat developed during deformation is partially transferred to the die which may be calculated as,

$$T_{Bd} = \Delta T \; \exp(-\alpha_T \; t / \rho \; C_p \; h) \tag{31}$$

The final temperature of the billet may be given by,

$$T_{Bf} = T_B + T_{BD} \tag{32}$$

Flash land

Due to the relatively small thickness of the flash as compared to the die cavity, the temperature gradient may be neglected. Thus, the average flash temperature may be calculated as,

$$T = T_{DC} + (T_{BC} - T_{DC}) \; \exp(-\alpha_T (t - t_{cont}) / \rho \; C_p \; \overline{t}) \tag{33}$$

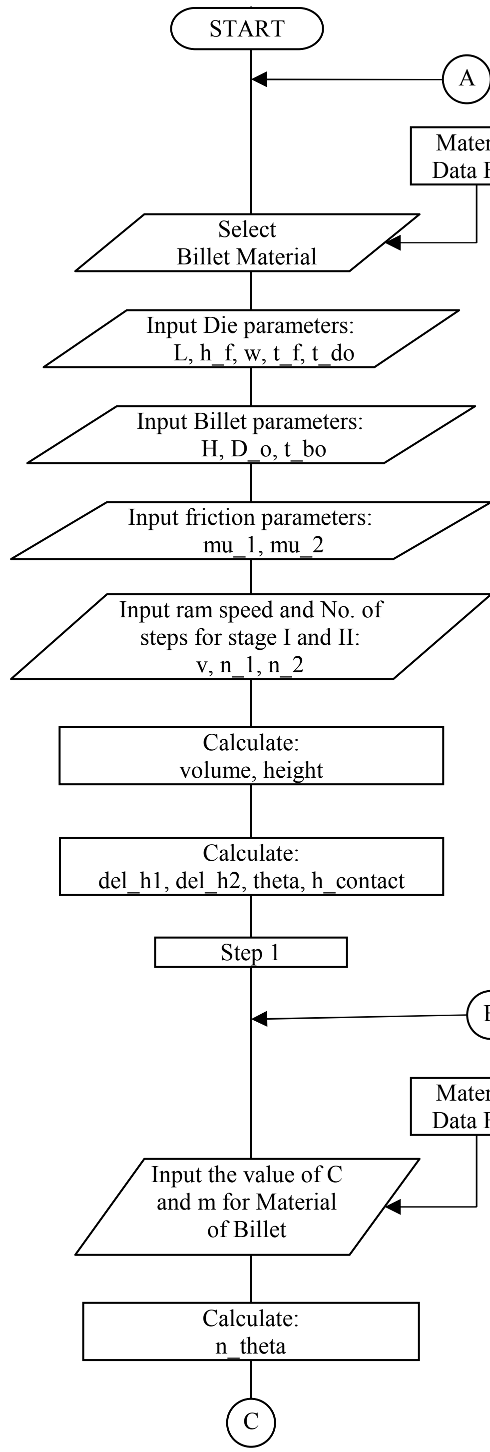
The final temperature in the flash is therefore,

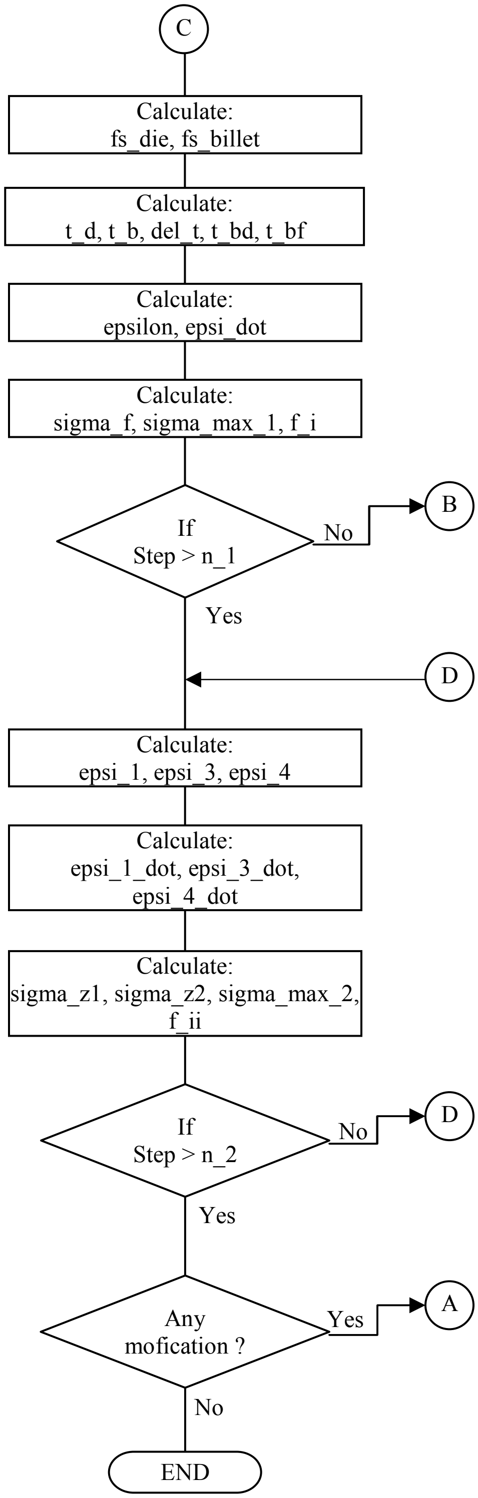
$$T_F = T + \Delta T \tag{34}$$

3. COMPUTER ALGORITHM

A computer simulation algorithm has been developed consisting of separate subroutines for the two different stages of forging process i.e. deformation process before flash formation and after flash formation [5], [8].

For the process simulation, initially the material is required to be selected from the material data base. The die parameters, billet parameters, number of stages of deformation process are required to be provided then the algorithm starts computations and simulations using computer graphics as per coding shown below [9], [10].





The computer code generates the results step by step for the various output parameters such as height, diameter, strain, strain rate, flow stress, force, temperature of die and billet.

At the end of the simulation, the algorithm asks for modifications, if any, may be the change of material or dimensions, for the purpose of next computations and simulation.

The application of this computer simulation method may be extended to more complicated parts such as a connecting rod of an Internal Combustion Engine as shown in Fig. 6 and forged components used in aero-engine [6], [7], [12].

Fig. 6 Connecting rod of I.C. Engine

4. RESULTS AND DISCUSSIONS

The results which were obtained based on the modeling method and computer algorithm, described in the previous sections, may be summarized as follows.

Fig. 7 shows the graph of flow stress and maximum stress plotted against the deformation steps for the billet H/D ratio of 1.23 and flash thickness of 2 mm. From the Fig. 7, it could be clearly seen that, as the deformation proceeds, the flow stress in the material steadily increases and the value of maximum stress also gradually increases. After a particular step, the increase in the maximum stress is steep; this is the point where the die cavity is almost filled and the flash formation starts.

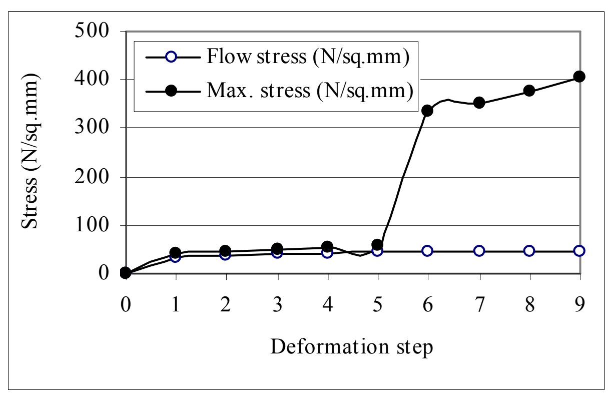


Fig. 7 Flow stress and Max. stress Vs. Deformation

Fig. 8 depicts the graphical representation of strain of billet plotted against the deformation steps. From the Fig. 8, it may be seen that, with the progress of deformation process, the strain in the material increases. During initial process of deformation i.e. deformation before flash formation, the increase in strain is more as compared to the deformation during the flash formation.

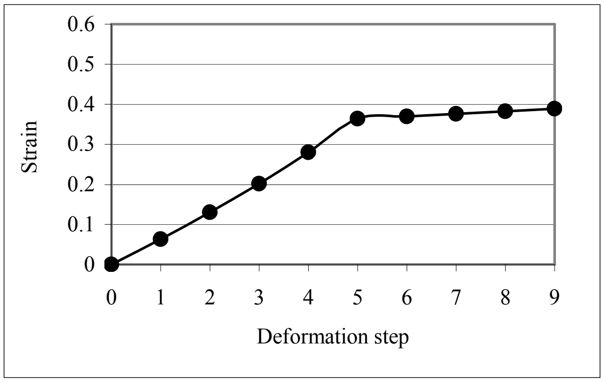


Fig. 8 Strain of billet Vs. Deformation

Fig. 9 shows the graph of variation of strain against the deformation steps during the flash formation process. The flash formation process starts when the die cavity gets almost filled and the extra material comes out resulting in to the flash formation. From the Fig. 9, it could be seen that, with the progress of deformation process, the strain in the flash continuously increases.

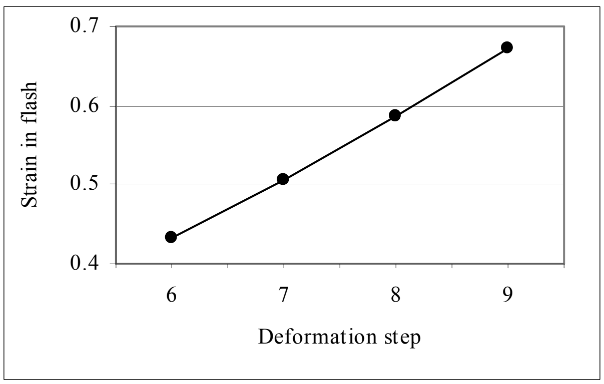


Fig. 9 Strain in flash Vs. Deformation

Fig. 10 represents the graph of variation in the die temperature and billet temperature against the deformation steps. From the Fig. 10, it could be clearly seen that, as the deformation proceeds, the billet temperature continuously keeps on decreasing and on the other side the die temperature keeps on increasing. This change in the temperatures of die and billet occurs in such a way that after some period of time, both, a die and a billet shall achieve the same temperature.

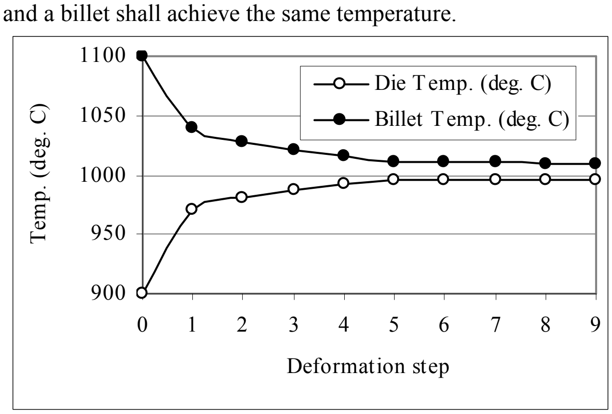


Fig. 10 Die and Billet temp. Vs. Deformation steps

From the Fig. 11, it could be clearly seen that, as the stroke proceeds, the load requirement for the deformation increases. At a particular stroke length, the increase in the load is steep; this is the point where the flash formation starts.

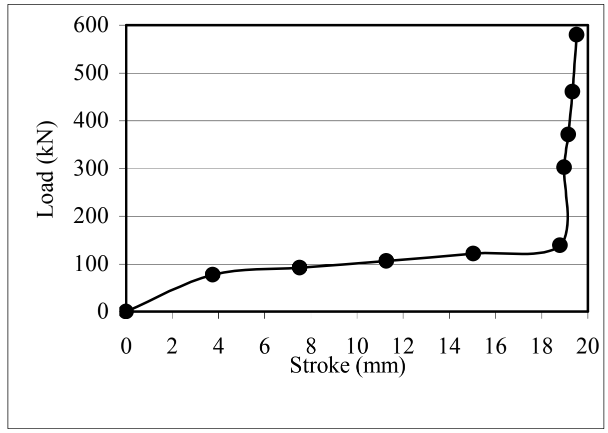


Fig. 11 Load (kN) Vs. Stroke (mm)

5. CONCLUSIONS

In the light of above graphical representations, the variation of the parameters such as flow stress, maximum stress, strain before flash formation, strain in flash, force, temperatures of die and billet have been found in good agreement with reference to their theoretical aspects discussed at the process modeling.

Finally, it may be concluded that the success of the simulation method would depend upon the following:

- The selection of material parameters from the material property database should match with the actual material. If the material properties are not known then it may be obtained by the suitable material testing method.
- The friction conditions considered in the computer simulation should be as close as possible to the conditions prevailing at the die-billet interface during the actual deformation process.

However, due to complexity of forging operations, the material and process conditions, the manufacturing by forging process is still very much dependent upon trial runs, which results into increased lead-time and cost. An integrated approach of combining the data obtained by the computer simulation method with that of the few trial runs could greatly optimize the closed die hot forging process and also contributes towards the efforts in reducing the global warming by lowering the energy consumption of the overall process.

6. NOMENCLATURE

C	Strain hardening constant
C_P	Specific heat of the material
D_o	Initial diameter of billet
F_I	Force required before flash formation
F_{II}	Force required after flash formation

H	Initial height of billet
$\bar{h}$	Current height of billet
$\bar{h}_c$	Average height of shearing zone at the beginning of flash formation
$\bar{h}_1$	Current average height of shearing zone
L	Die diameter
m	Strain rate sensitivity exponent
t_i	Initial distance between flash lands of two die halves
t	Deformation time
t_{cont}	Time of contact or start of flash formation
$\bar{t}$	Flash thickness
$\bar{t}_c$	Flash Thickness at the beginning of flash formation
T_{BO}	Initial billet temperature
T_B	Current billet temperature
T_{Bd}	Temperature rise of the billet due to deformation
T_{DO}	Initial die temperature
T_D	Current die temperature
ΔT	Increase of temperature due to deformation
v	Ram speed
w	Flash width
α_T	Heat transfer co-efficient between die and billet
β	Shear plane angle
ε	Strain before flash formation
ε_1	Strain for zone 1
ε_3	Strain for zone 3
ε_4	Strain for zone 4
$\dot{\varepsilon}$	Strain rate before flash formation
$\dot{\varepsilon}_1$	Strain rate for zone 1
$\dot{\varepsilon}_3$	Strain rate for zone 3
$\dot{\varepsilon}_4$	Strain rate for zone 4
ε_{tc}	Strain at the beginning of the flash formation
θ	Time in seconds
λ	Thermal conductivity of the billet material
μ_1	Coefficient of friction between die and billet
μ_2	Coefficient of shearing friction
ρ	Density of the material
σ_f	Flow stress
σ_{max1}	Maximum stress before flash formation
σ_{max2}	Maximum stress after flash formation

Encircled digits 1, 2, 3, and 4 indicate respective zones in Fig. 3.

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