STUDIA UBB PHYSICA, Vol. 61 (LXI), 1, 2016, pp. 35-46
(RECOMMENDED CITATION)

Dedicated to Professor Dr. Cozar Onuc on His 70th Anniversary

FINITE ELEMENT ANALYSIS OF FRICTION PARAMETERS ON 6060 ALUMINIUM ALLOY IMPRESSION DIE COLD FORGING PROCESS

M. POP[a,*], D. FRUNZA[a]

ABSTRACT. In this paper cold forging process of aluminium alloy 6060 is simulated and analyzed at different stages of forging and with different quality of lubricants. Finite element (FE) method is extensively employed in solving linear and non-linear problems and widely used particularly in analyzing a forming process. Three-dimensional modeling of initial material and die are performed by Solid Works, while simulation and analysis of forging are performed by Forge. Based on the computer simulation the required dies are designed and the workpieces are formed.

Keywords: *Aluminium alloy, Impression die forging, FE analysis, Simulation.*

INTRODUCTION

One of the major concerns in the research of manufacturing processes is to find the optimal production conditions in order to reduce production costs and lead time. In order to optimize a process, the effect of the most important process parameters has to be investigated. Conducting experiments, can be very time consuming and expensive. Therefore, various computational methods have been developed and used to reduce the number of necessary experiments. One of these methods, FEM, has proved to be the most powerful analysis tool. With the increasing use of computers in industry, FEM has steadily gained importance in the simulation of metal-forming processes.

Cold forging is an essential process and widely used in a typical manufacturing production. In the process, the metal is continuously pressed under high pressure into high strength parts and as a result, the material experienced extensive plastic deformation during the progression.

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[a] *Technical University, Faculty of Materials Engineering and Environment, B-dul Muncii 103-105, Cluj-Napoca, Romania*

[*] *Corresponding author: Mariana.Pop@ipm.utcluj.ro*

Besides, cold forging has a high performance on the production rate and repeatability. The parts with cold forging process are largely produced at high rate compare to those achieved by the machining processes as the parts are immediately ready for use after the forging; the process is conducted by automated production lines that directly converts the workpiece to the finished parts. The repeatability of the process becomes excellent with optimal die design, low temperature and optimal lubrication [1,7,8]. Another important advantage of cold forging process is the amount of waste material for finished part is very insignificant. The process is a "chipless machining", in which sometimes requires less or no cutting process as well as eliminates secondary grinding.

The prediction of material flow can be achieved completely by computer simulation. Main parameters in computer simulation are filling the die completely without leaving any defect, reducing material loss and stress in die and increasing die life.

Finite element analysis (FEA) has been developed during the last decades as a very useful tool for analysis of metal forming processes [2,3,4,9]. Recent progress in FEA, together with increasingly powerful computers, has permitted increased use of such numerical modeling. Hence, today it is possible to FEM-simulate the metal forming processes at various design stages.

Process modeling of closed-die forging using finite-element modeling (FEM) has been applied in aerospace forging for a couple of decades [2].

Aluminum alloy A6060 is one of the most used high-strength material for aircraft structural components. Also is commonly used for architectural sections for windows, doors, curtain walls, interior fittings, lighting, furniture and office equipment, structural applications where surface finish is important.

Friction has an important influence in metalforming operations, as it contributes to the success or otherwise of the process. In the present investigation, the effect of friction on metal forming was studied by simulating close die forging on AA6060 aluminium alloy using the finite element method (FEM) technique. However, the coefficient of friction between the die–work-piece interfaces was varied. It was concluded that the variations in the coefficient of friction between the dies and the work-piece directly affect the strain, stress distribution and deformation force.

The present study used rigid-plastic finite element (FE) Forge software to investigate the plastic deformation behavior of an aluminum alloy (A6060) workpiece.

THEORETICAL ASPECTS

Figure 1 present the impression die forging principle.

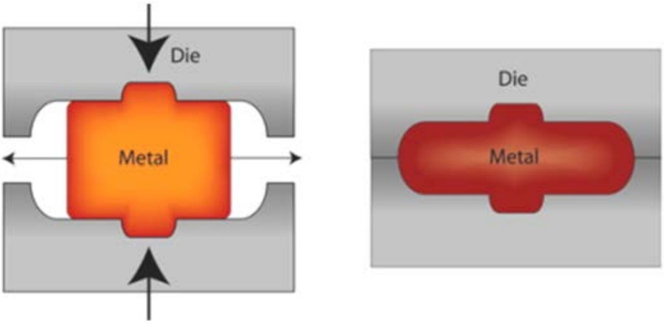


Fig. 1. Impression die forging principle.

During the forging process, metal flow, die fill, and forging load are largely determined by the flow stress of the forging materials, the friction and cooling effect at the die/material interface, and the complexity of the forging shape.

The interrelationships of the most significant forging variables are illustrated in the block diagram in Fig. 2.

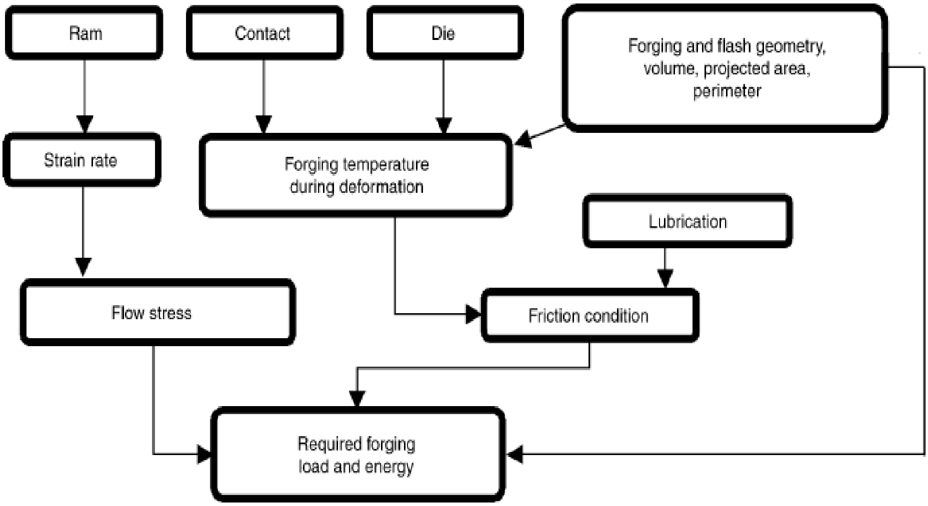


Fig. 2. Interaction of significant variables in impression die forging process [2].

In metal forming, friction is a crucial factor that determines whether an industrial process can be run with acceptable, economic result.

The basic function of any lubricant is to reduce friction between two surfaces and to reduce wear. In the case of forging, a good forging die lubricant must have the following properties: reduce friction, reduce forging load, enable uniform metal flow to fill the die cavity, serve as a barrier to heat transfer.

In impression die forging the metal is confined in between two dies. Under these circumstances, the contact pressure rise much higher than the flow stress of the workpiece material. Under high contact pressure, the Coulomb friction model may fail to describe the actual friction conditions. A friction model different from the Coulomb model is the Tresca friction model. This model is able to give a better description of the friction over the workpiece–die interface in the case of high contact pressures. These friction models have been developed for quantitative evaluation of friction in bulk metal forming, and are applied in FE analysis [10]. Coulomb friction model based on Amonton's law can be expressed as:

$$\boldsymbol{\tau = \mu\sigma} \tag{1}$$

where τ is the frictional shear stress, m the coefficient of friction at the die/workpiece interface, σ the normal stress.

Tresca's friction model is commonly expressed the following way:

$$\boldsymbol{\tau = mk = \frac{m}{\sqrt{3}}\sigma_c} \tag{2}$$

where m is the frictional shear factor, K the shear yield strength, if m=1, then $\tau = \tau_{max}$ = K for the condition of maximum friction force, namely sticking friction, whereas m=0 for a frictionless condition, σ_0 is shear flow stress of the workpiece material.

SIMULATION DETAILS

The tensorial form of the Norton-Hoff law used in FORGE 3® is written as [9]:

$$s = 2A(T, \bar{\varepsilon}, \ldots)(\sqrt{3} * \dot{\bar{\varepsilon}})^{m-1} \dot{\varepsilon} \tag{3}$$

$$A(T, \bar{\varepsilon}) = A_0 * (\bar{\varepsilon} + \bar{\varepsilon}_0)^n * e^{\frac{\beta}{T}} \tag{4}$$

where ***s*** is the deviatoric stress tensor, A is the consistency of material, $\bar{\varepsilon}$ is the equivalent strain, m is the strain rate sensitivity, $\dot{\varepsilon}$ is the equivalent strain rate, β is the material constant, n is the strain hardening index and $\bar{\varepsilon}_0$ is a small constant.

The flow formulation introduced by Hensel and Spittel is written as:

$$\sigma = A * e^{m_1 T} * T^{m9} * \varepsilon^{m2} * e^{m4/\varepsilon} * (1+\varepsilon)^{m5T} * e^{m7\varepsilon} * \dot{\varepsilon}^{m3} * \dot{\varepsilon}^{m8T} \tag{5}$$

where m_1, m_2,..m_9 are sensitivity parameters.

A simulation of the close die forging process was performed using the finite element software. This was achieved by constructing an accurate three dimensional CAD model of the process. The model was meshed with appropriate elements and material properties and boundary conditions were added. The geometries of the billet and dies, were generated in SolidWorks and the meshes within their space domains in FORGE 3D. The physical properties of the aluminium alloy used in the computer simulation are given in Table 1. The billet was considered thermo-viscoplastic while the tools rigid, and both of these material models neglected the elastic deformation. The shear-type friction conditions at the workpiece and tooling interfaces were imposed as part of the boundary conditions.

Table 1.

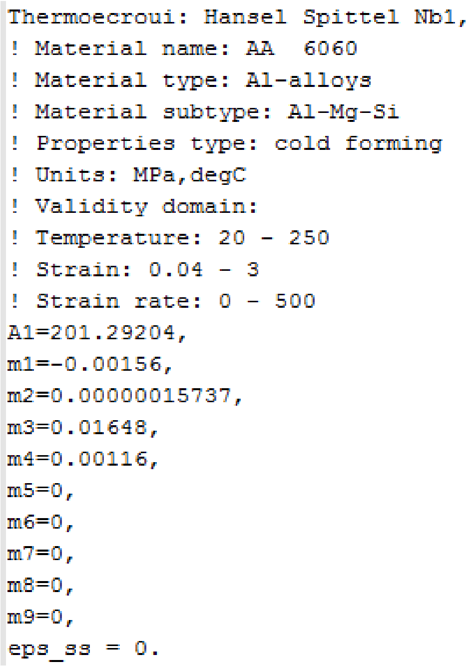
Properties	Material A6060
Density (kg/m^3)	2800
Heat capacity (N/m^2 ^{0}C)	2,39
Thermal conductivity (W/mK)	250
Emissivity	0,05

The process parameters used in the simulations are given in Table 2.

Table 2.

Billet height [mm]	15
Billet diameter [mm]	40
Upper die speed [mm/s]	0,5
Friction factor at the workpiece–die interface	0,1;0,3;0,4
Billet temperature [^{0}C]	20
Dies temperature [^{0}C]	20

The geometries of the billet, die, container and ram were generated in SolidWorks and the meshes within their space domains in FORGE 3D. Fig. 3 shows the initial meshes of the billet and the tooling, together with a cross-section cutting through the die. The die had a rotational symmetry, which allowed one-quarter of objects to be modelled in order to save computing time. The present analysis adopts the following assumptions: (1) the mold and die are all rigid bodies; (2) the aluminum alloy (A6060) billet is a rigid-plastic material. The parameters from the constitutive equation are presented below.



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Thermoecroui: Hansel Spittel Nb1,
! Material name: AA  6060
! Material type: Al-alloys
! Material subtype: Al-Mg-Si
! Properties type: cold forming
! Units: MPa,degC
! Validity domain:
! Temperature: 20 - 250
! Strain: 0.04 - 3
! Strain rate: 0 - 500
A1=201.29204,
m1=-0.00156,
m2=0.00000015737,
m3=0.01648,
m4=0.00116,
m5=0,
m6=0,
m7=0,
m8=0,
m9=0,
eps_ss = 0.
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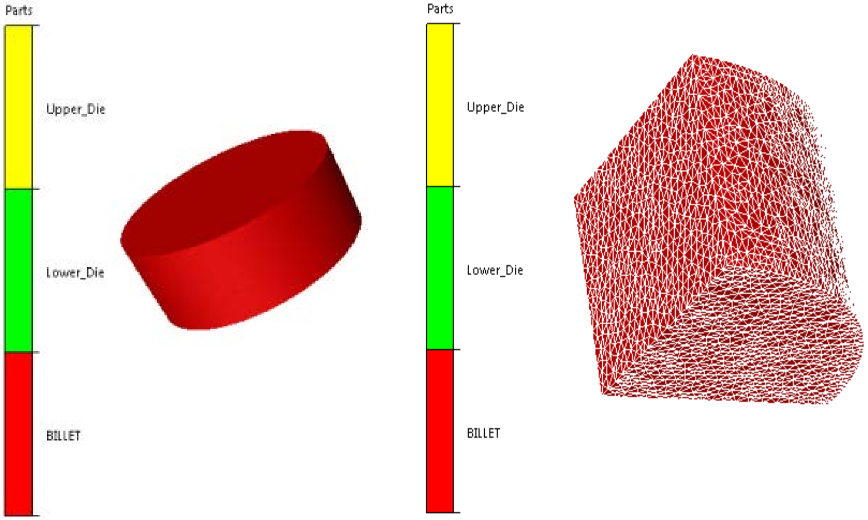
Fig. 3 shows the initial mesh of the billet and the geometrical model of the dies.



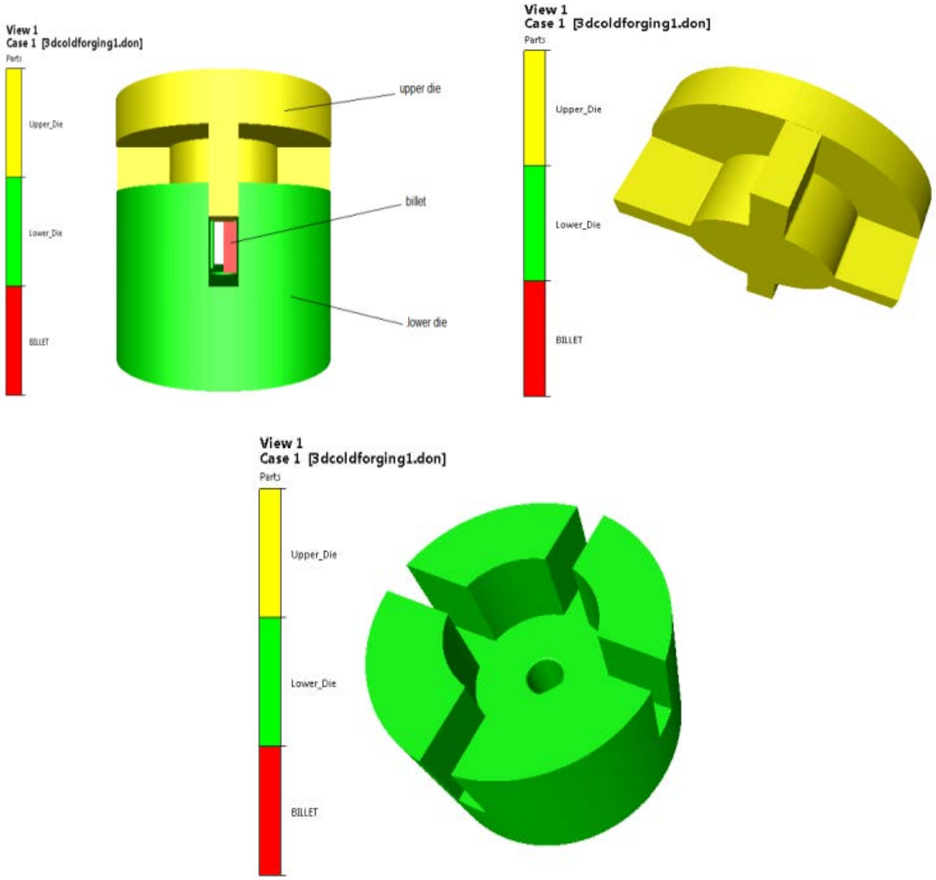


Fig. 3. Initial mesh of the billet, and the geometrical models of the dies.

RESULTS AND DISCUSSIONS

After the model has been created, a number of simulations were run to study the effect of lubrication conditions on the metal flow. The results obtained for equivalent strains, von Mises stress, energy exchange due to friction and deformation force distribution in different lubrication conditions are presented in figures below.

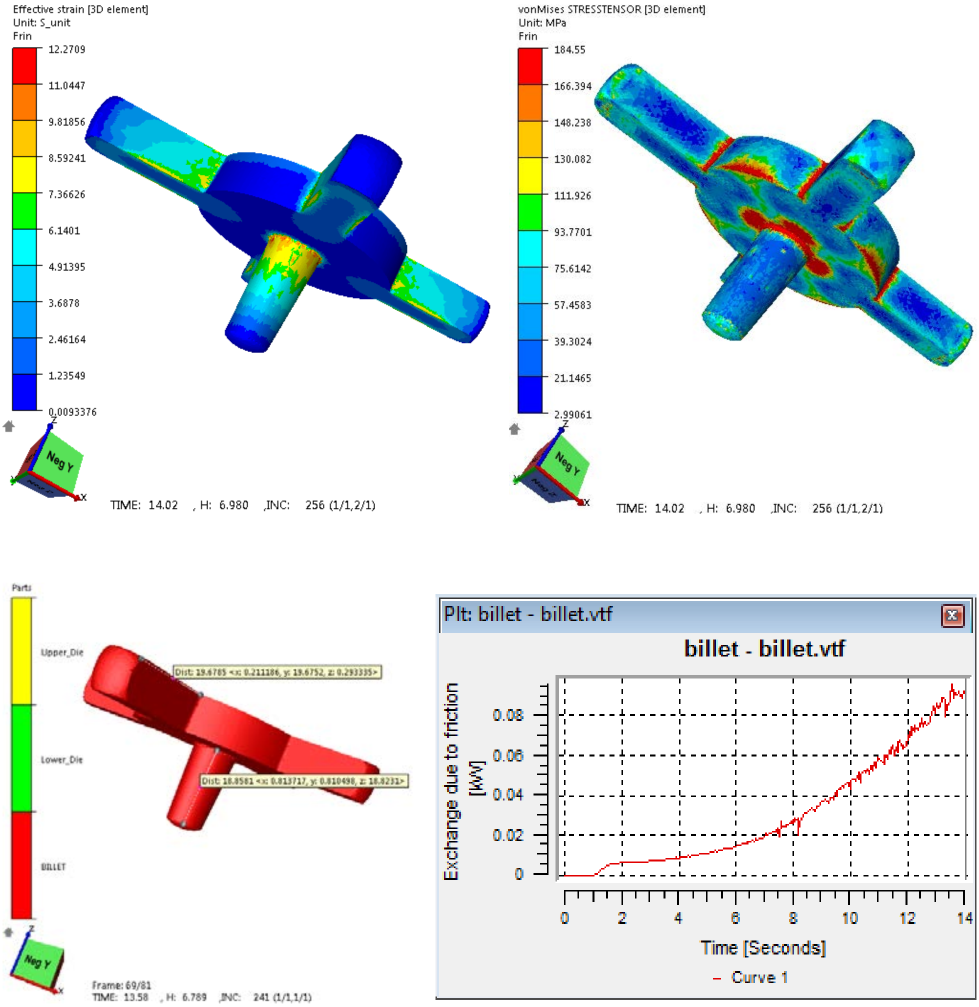


Fig. 4. Distribution of effective strain, von Mises stress and exchange energy due to friction in the billet for friction coefficient μ=0,4.

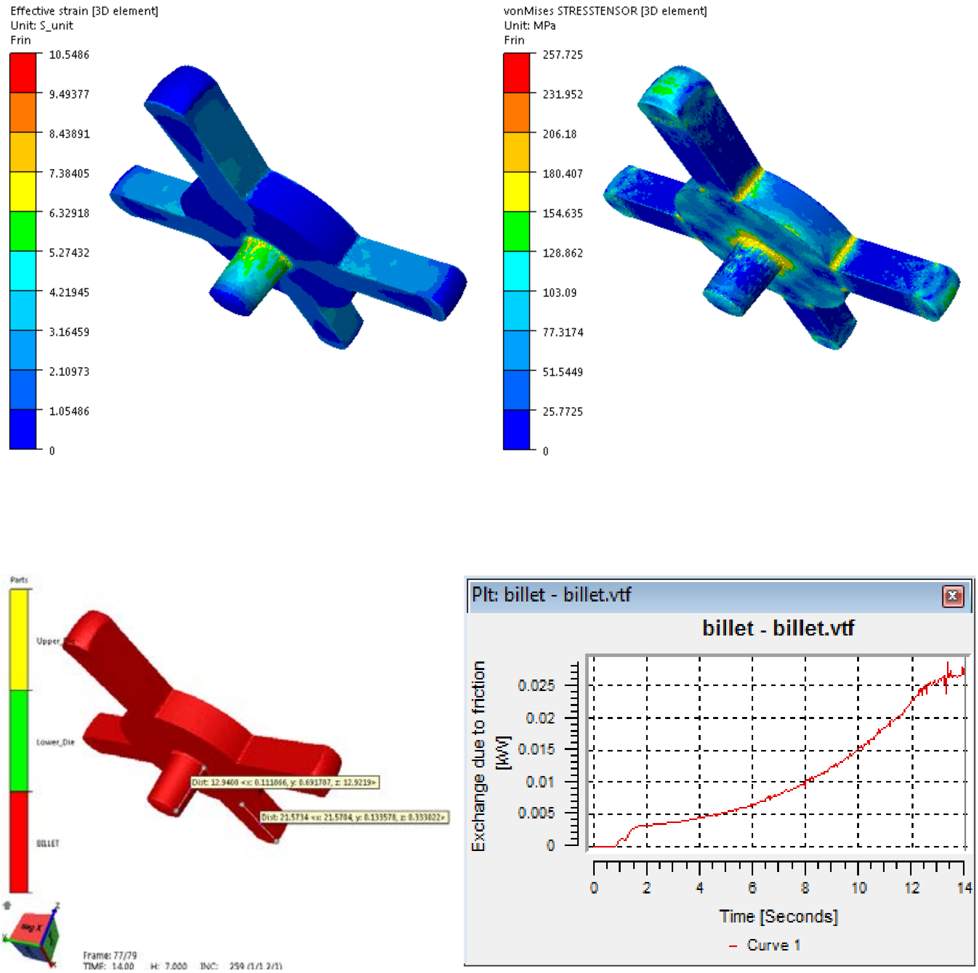


Fig. 5. Distribution of effective strain, von Mises stress and exchange energy due to friction in the billet for friction coefficient μ=0,1.

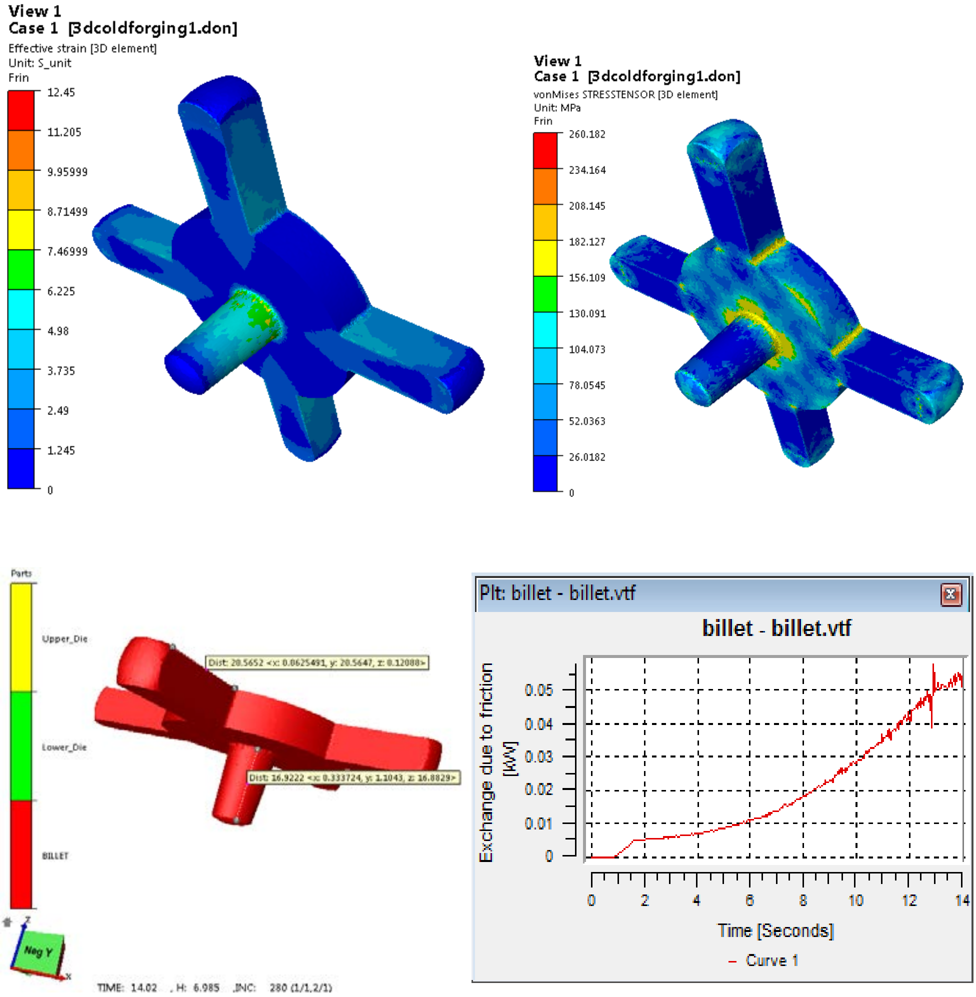


Fig. 6. Distribution of effective strain, von Mises stress and exchange energy due to friction in the billet for friction coefficient μ=0,2.

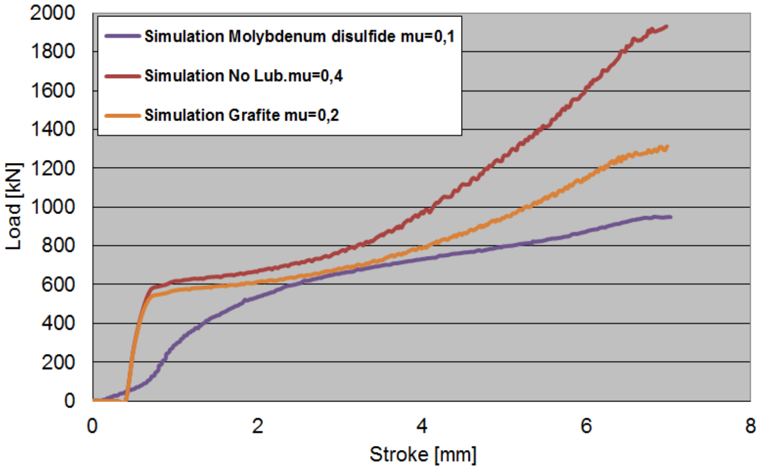


Fig. 7. Deformation force distribution.

By referring to Fig.7; it indicates that the total forming load was increased with the values of friction coefficient. The highest maximum forming load was produced when no lubrication is used, which has the highest friction coefficient value. On the other hand, the lowest maximum forming load was generated as molybdenum disulfide was applied. It was found that the forming load values exhibited by no lubrication, graphite, and molybdenum disulfide were 1900kN, 1300 kN and 950 kN, respectively. It has been evaluated from the FE results that the forming load was found to be proportional to the friction coefficients, as the friction values increased, the die life decreased as higher friction coefficients required higher load to fill the die cavity. Based on the analyses, the friction utilized in the die design to a great extent influenced the metal flow as it can be seen in figures 4,5 and 6. By increasing the coefficient of friction from 0,1 to 0,4 increases also the effective strain and von Mises stress. The increase in von Mises stress value determine an increase in die wear and the fatigue life would be reduced. From the analysis, the highest maximum stress in the billet was found as 185 MPa with friction coefficient of 0.4, whilst the lowest value of maximum stress was 154 MPa with friction coefficient value of 0.1.

In summary, the optimal value of friction coefficient in impression die cold forging of A6060 aluminium alloy was 0.1, in which the lubricant consisted of molybdenum disulfide.

CONCLUSIONS

Computer-aided engineering (CAE) simulation is a useful tool to optimize, validate, verify and hence, generate the design solutions before they are implemented. The results can be utilized to analyze the tool design and forming processes during the designing stage as well as in the trouble shooting stage. In the current study, the effect of friction coefficients were studied on the material flow in impression die cold forging. Workpiece and die assembly components were constructed in the CAD models before the commercial FEM-code ForgeTM was implemented.

It has been evaluated from the FE results that the forming load was found to be proportional to the friction coefficients, as the friction values increased, the die life decreased as higher friction coefficients required higher load to fill the die cavity.

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