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Finite element analysis of superalloys forward extrusion

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Numerical simulation is becoming an important tool for forming process development. In the field of metal forming, bulk forming has been widely analysed. In this paper, numerical simulations are conducted to analyse the process of Incoloy 901 forward extrusion. The FEA simulation was carried out using Forge3, a FEA software, specifically produced for metal forming simulation. An axisymmetrical 3D geometric model of tools and billet was constructed for the analysis. The extrusion speed was varied and also the extrusion die angles. The influence of die angle, reduction ratio, ram speed, die temperature on the extrusion force during the extrusion process were investigated. Results show that die angle, ram speed, die land diameter has a significant influence on the extrusion force evolution. The simulation results confirm the suitability of the current finite element software for modeling the three-dimensional extrusion of aluminum billets.

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Keywords: Finite element analysis, Forward extrusion, Superalloys

1. Introduction

Superalloys are a group of nickel, iron–nickel and cobalt alloys used in aircraft turbine engines for their exceptional heat-resistant properties [1]. Materials used in jet engines must perform for long periods of time in a demanding environment involving high temperature, high stress and hot corrosive gas. Superalloys, possess many properties required by a jet-engine material such as high strength, long fatigue life, fracture toughness, creep resistance and stress-rupture resistance at high temperature. In addition, superalloys resist corrosion and oxidation at high temperatures, which cause the rapid deterioration of many other metallic materials [2].

In general, the alloying elements that are routinely added to superalloys to raise hot strength degrade hot and cold ductility at certain processing regimes. The material workability is therefore controlled by the influence of alloying elements on the microstructural mechanisms during hot or cold deformation. It is generally accepted that the hot workability of alloys decreases as their alloy content increases. Alloying elements often interact with the restoration mechanisms of dynamic recovery (DRV) or dynamic recrystallization (DRX) through making fine precipitates or exerting a solute drag force on the moving boundaries. On the other hand, the occurrence of DRV or DRX is essential to avoid strain accumulation and to assure a stable flow during hot deformation. Therefore, the higher alloy content, the less efficient restoration processes which manifests the need for the exact design of hot deformation regime in order to avoid any flow instability [3].

The final mechanical properties of Ni-based superalloys depend not only on the processing parameters (deformation temperature, strain rate, deformation degree, etc.), but also on the initial microstructures (grain size, second phases, etc.). Therefore, in order to obtain the optimal mechanical properties of workpieces, it is important to study the flow behaviors and microstructural evolution during the hot deformation of Ni-based superalloys [4]. In recent years, many investigators have studied the flow behaviors and microstructural evolution of Ni-based superalloys [5,6].

Extrusion is one of the most important metalworking processes. Extrusion produces compressive and shear forces in the billet. No tensile force is produced, which make high deformation possible. Geometrical characteristics of the extrusion die influence both the extrusion process and the mechanical properties of the extruded material. Experimental investigations have been made to achieve the effect of die reduction ratio, die angle on the quality of extruded parts. Previous research has shown that extrusion die geometry, frictional conditions at the die billet interface and thermal gradients within the billet greatly influence metal flow in extrusion [7].

Finite element analysis (FEA) has been developed during the last decades as a very useful tool for analysis of metal forming processes [8,9,10,11,12]. Progress in development of cheap and efficient computer technology, and the implementation of the finite element method (FEM) into user-friendly, window-based programs, has brought this technology forward. When a FEM model has been made for a particular forming application, the load requirement, velocity, strain rate, strain and stress fields, etc., can easily be obtained for the considered process. However, the accuracy of such simulations will remain dependent on the reliability of the material data, most important of all the true flow stress.

The present study employs FORGE 3D finite element code to predict the force evolution throughout the whole cycle of extruding a Incoloy 901 billet.

2. Theoretical aspects

Constitutive equations are used to describe the changes in strength observed to occur in materials being deformed. These formulations are empirical and relate changes in strength produced by variation in strain, temperature or strain rate. Such equations are used to predict forces, distortions, stresses, etc. that can be encountered during mechanical processing of materials. The general form of constitutive equation is:

$$\bar{\sigma} = f(\varepsilon, \dot{\varepsilon}, T, \sigma^*) \tag{1}$$

where: σ, true stress; ε, true plastic strain; $\dot{\varepsilon}$, strain rate; T, temperature; σ^*, parameter dependent of the history of deformation, respectively.

Considerable efforts have been carried out over decades to develop quantitative constitutive relations which describe the flow strength of materials as a function of process variables, i.e., strain, strain rate and temperature, for the correct modeling of processes. The techniques for extrusion of different materials are dependent, to a large extent, on the extrusion temperature. The essence of hot working is to reduce the yield stress and thus increase extrusion speed for a given press force. Critical parameters for successful and economical hot extrusion include the method of billet preparation and heating, the amount of pressure and rate of speed used for extruding, and the type of lubricant employed. A billet temperature that is too high can cause blisters or other surface defects, including cracking. A temperature that is too low increases the pressure requirements for the extrusion and shortens tool life. An important advantage of extrusion is that it produces compressive and shear forces in the billet; no tensile force is produced, which makes high deformation possible. Figure 1 present the forward extrusion principle [13].

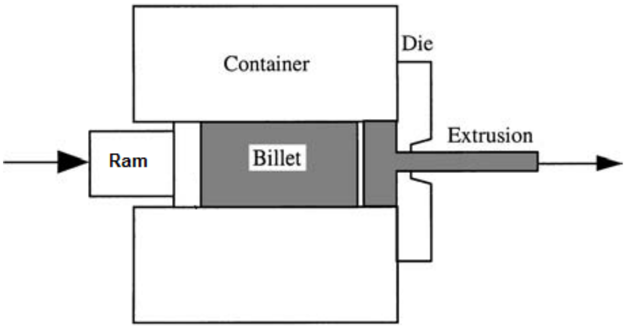


Fig.1 Forward extrusion principle.

Forge is a commercial software developed at CEMEF, Ecole des Mines de Paris and is used for the analysis of plastic deformation processes. The program is based on the finite element method for cold and hot metal forming. It enables the thermo-mechanical simulation of the plastic deformation processes of metals in an axisymmetric, homogeneous and isotropic state of deformation and obeys the von Mises criterion. The calculations of the metal flow, stress field, strain, strain rate and temperature are conducted on the assumption of the visco-plastic model of the deformed body.

The tensorial form of the Norton-Hoff law used in FORGE 3® is written as [7]:

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

$$A(T, \bar{\varepsilon}) = A_0 * (\bar{\varepsilon} + \bar{\varepsilon}_0)^n * e^{\frac{\beta}{T}} \tag{3}$$

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:

$$\sigma = A * e^{m_1 T} * T^{m9} * \varepsilon^{m2} * e^{m4/\varepsilon} * (1+\varepsilon)^{m5T} * e^{m7\varepsilon} * \dot{\varepsilon}^{m3} * \dot{\varepsilon}^{m8T} \tag{4}$$

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

The extrusion process parameters including die geometry and ram speed has an important influence on material flow during the deformation. The material flow affects the product quality (structure and properties) and the extrusion load.

3. Simulation details

Incoloy 901 is a Ni–Fe superalloy that is widely used at high temperature industries such as airplane engines and gas turbines [14]. High strength is imparted to this alloy by the solid solution of alloying elements (like Fe, Cr, Mo, Ti, Al and Co) as well as the precipitation of Ni–Al–Ti intermetallic compounds. In general, the alloying elements that are routinely added to superalloys to raise hot strength, degrade hot and cold ductility at certain processing regimes. The material workability is therefore controlled by the influence of alloying elements on the micro- structural mechanisms during hot or cold deformation. A substantial iron content enables the alloy to combine high strength with good forging characteristics. A schematic illustration of the forward extrusion process is presented in figure 2. A simulation of the extrusion 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.

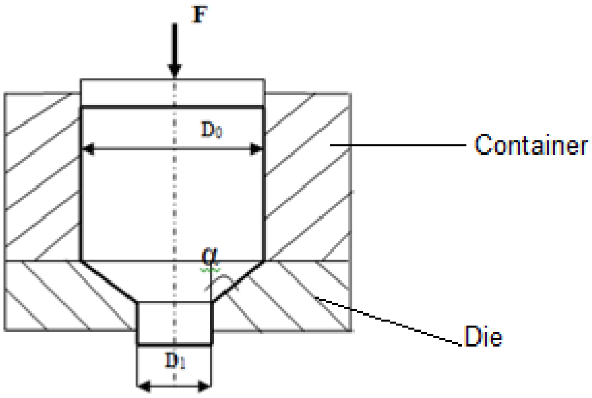


Fig.2. Schematic illustration of the forward extrusion process.

The geometries of the billet, die, container and ram were generated in SolidWorks and the meshes within their space domains in FORGE 3D. The physical properties of the Incoloy used in the computer simulation are given in Table 1. The billet was considered thermo-viscoplastic, 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. The friction factor, according to Tresca friction law, at the billet–die interfaces were assumed to be 0,3.

Tabel 1

Properties	Material Incoloy 901
Density (kg/m^3)	8140
Specific heat (J/kg K)	431
Thermal conductivity (W/mK)	11,4
Emissivity	0,58

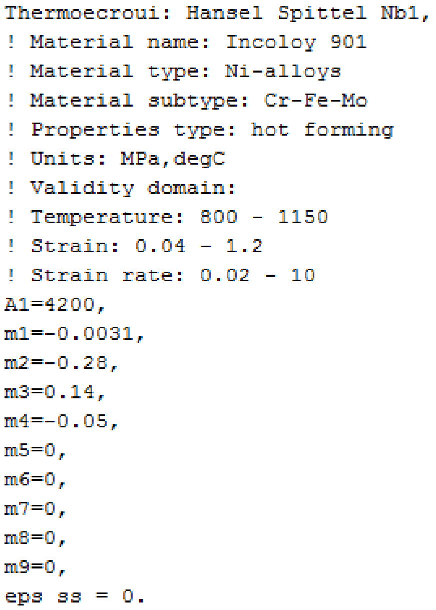
The process parameters used in the simulations are presented in Table 2.

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.

Table 2

Billet height [mm]	30
Billet diameter [mm]	30
Die semi angle α [^{0}]	60,70,80,90
Extrusion ratio	2,4,6
Billet temperature [^{0}C]	1000
Container and die temperature [^{0}C]	300
Ram speed [mm/s]	2,4,6
Friction factor at the workpiece die interface	0,3

The parameters from the constitutive equation are presented below.



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Thermoecroui: Hansel Spittel Nb1,
! Material name: Incoloy 901
! Material type: Ni-alloys
! Material subtype: Cr-Fe-Mo
! Properties type: hot forming
! Units: MPa,degC
! Validity domain:
! Temperature: 800 - 1150
! Strain: 0.04 - 1.2
! Strain rate: 0.02 - 10
A1=4200,
m1=-0.0031,
m2=-0.28,
m3=0.14,
m4=-0.05,
m5=0,
m6=0,
m7=0,
m8=0,
m9=0,
eps ss = 0.
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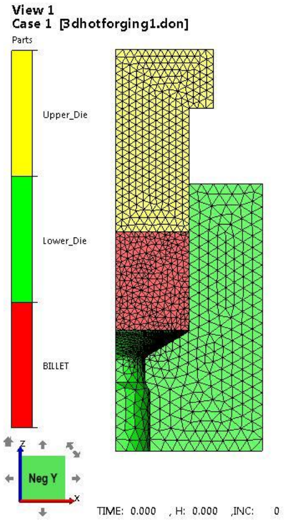
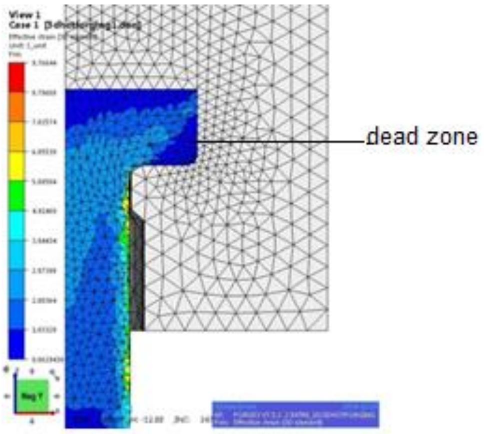


Fig.3. Initial meshes of the billet, container, die and ram and the cross-section of the die (one-quarter of the objects)

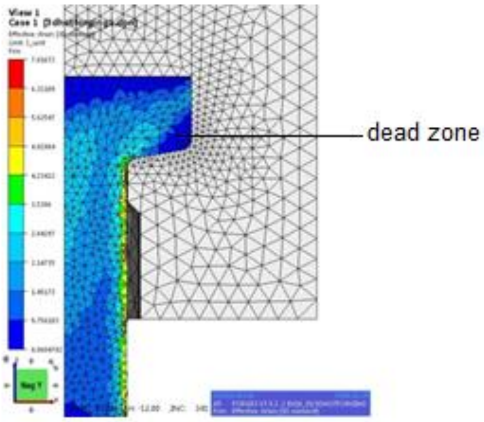
4. Results and discussions

Fig. 3 shows the die and the container which was modeled simplified as one single tool. After the model had been created, a number of simulations were run to study the effect of various extrusion parameters on the metal flow, using flow stress data. The input parameters (friction, thermal conditions of billet and container, geometrical parameters of the die, ram speed) were varied within a realistic range.

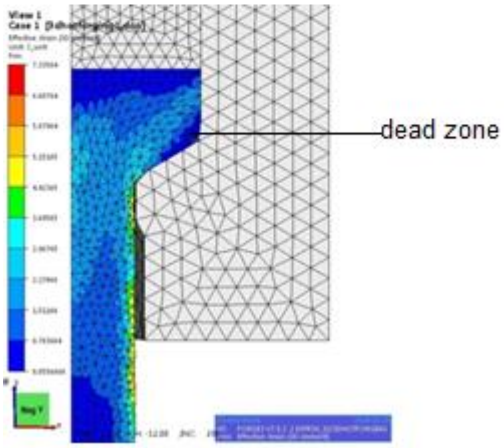
The results obtained for strain and extrusion force distribution in different extrusion conditions are presented in figures below.



a. α=90^0



b. α=80^0



c. α=60^0

Fig. 4. Effective strain distribution for different die angles, by using ram speed 6mm/s and die land diameter D=15 mm.

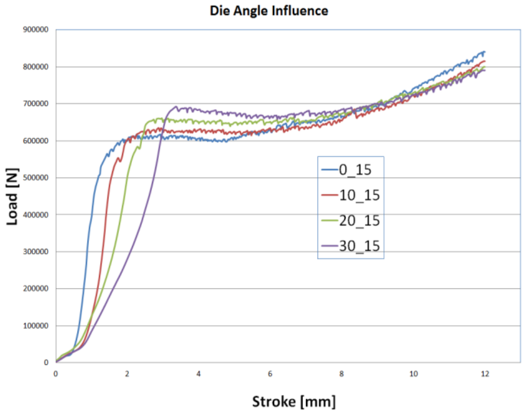
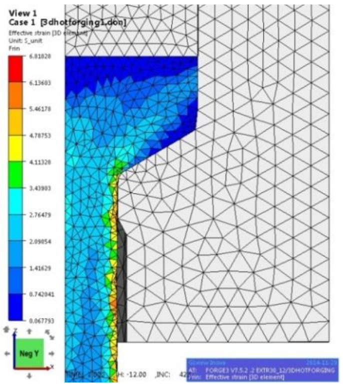
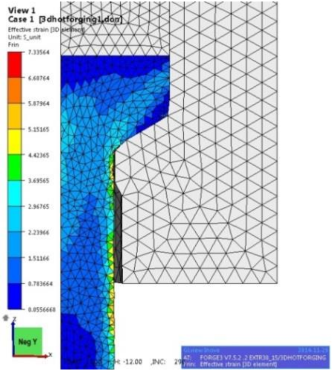


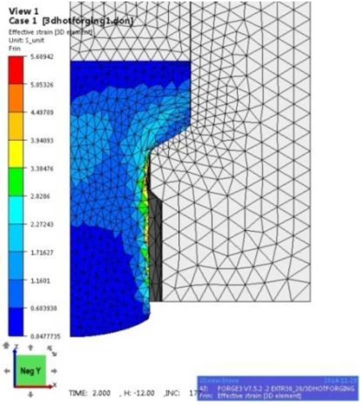
Fig.5. Extrusion force distribution function of stroke for different die angles,by using ram speed 6 mm/s and die land diameter D=15 mm.



a. D_1=12mm



b. D_1=15 mm



c. D_1=20 mm

Fig.6. Effective strain distribution for different die land diameter D , by using die angle 60^0 and ram speed 6 mm/s.

The distribution of the effective strain inside the billet at a particular stage of extrusion was determined by the simulation model (Fig.4, Fig.6, and Fig.8). As these figures depicts, two zones of different deformation characteristics become visible in the interior of the billet. In addition to the dead zones in the corner between the die and the container and adjacent to the ram, there is also a tertiary dead zone in the core of the billet.

The influence of the die semi-angle on the extrusion load is presented in figure 5. The curves indicate the three stages of extrusion: compression, steady and unsteady stages.

Fig. 7 shown the influence of die land diameter on extrusion load. By increasing the die land diameter from 12 mm to 20 mm (decreasing the reduction of area) the extrusion load decrease.

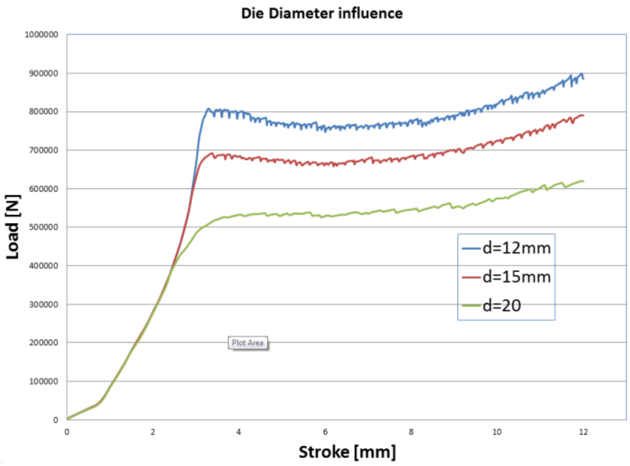
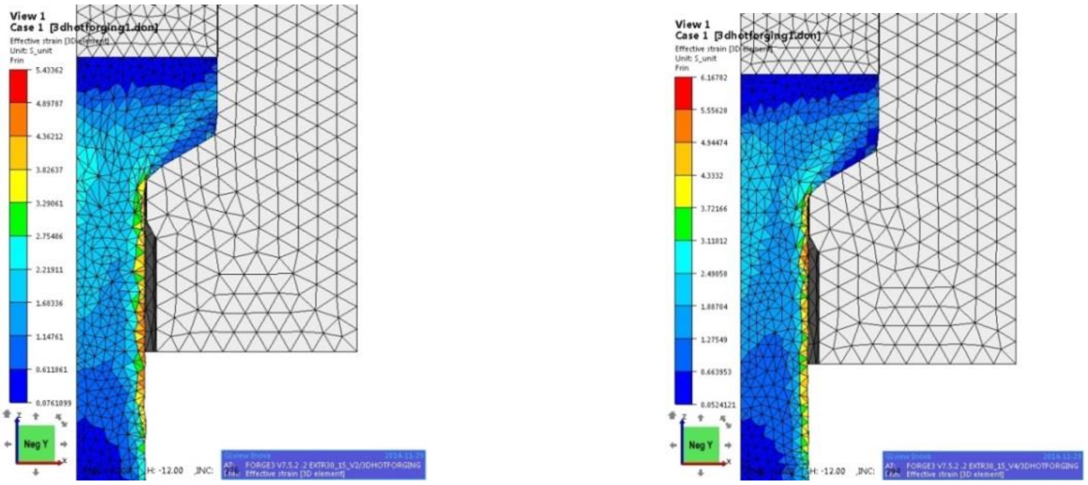
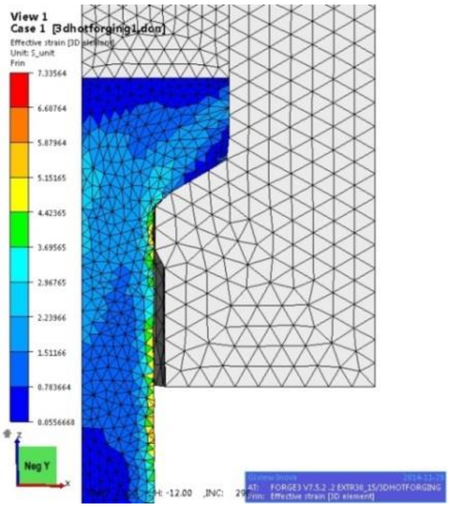


Fig.7. Extrusion force distribution function of stroke for different die lands diameters d, by using die angle 60^0 and ram speed 6 mm/s, respectively.



a. v=2 mm/s

b. v= 4 mm/s



c. v= 6 mm/s

Fig.8. Effective strain distribution function of different ram speed v, for die angle 60^0 and die land diameter 15 mm.

The influence of ram speed on extrusion force is presented in figure 9. Ram speed has a significant influence on the extrusion load, which continuously changes throughout the process.

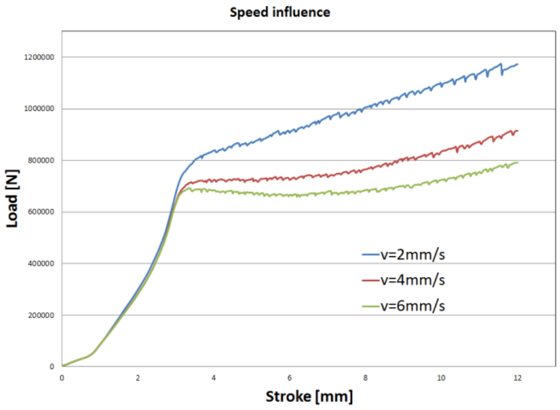


Fig.9. Force distribution function of stroke for different ram speed v, by using die angle 60^{0}and die land diameter 15 mm, respectively.

The higher value of extrusion load to a ram speed of 2mm/s can be explained as a result of complex heat generation during the deformation. At a lower ram speed, the increase of extrusion load is due to heat exchange between the hot billet and cold die and thus increased flow stress, as the process proceeds. To make best use of the force capacity of the press and to approach the highest possible extrusion speed without leading to extrusion defects caused by incipient melting, it is necessary to select an optimum ram speed at a given billet temperature.
The influence of billet temperature on extrusion load is shown in figure 10. The thermal effect results in characteristic variation of extrusion load. By increasing the billet temperature from 900 ^{0}C to 1100 ^{0}C, the material formability and the deformation load increase.

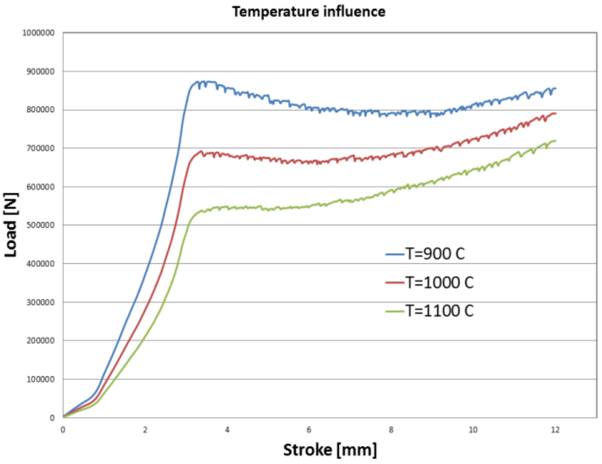


Fig.10. Force distribution function of stroke for three billet temperature T, by using die angle 60^0 and die land diameter 15 mm, respectively..

5. Conclusions

This study has utilized three-dimensional finite element code to examine the plastic deformation behavior of an incoloy billet during its axisymmetric direct extrusion through flat and conical die.

The numerical results have shown the following:

- die geometry, ram speed and temperature has a significant influence on uniform deformation of material and also on the extrusion load

- effective strain, is small in the core of the billet ($\varepsilon <$ 2) and considerably larger in the surface layer of the billet ($\varepsilon > 4$), where the shear zone is present. For a die ange α = 90 °, there are present large dead zones (with no plastic deformation) and a nonuniform material flow due to high friction between billet and container and billet and die. By reducing the die angle to 80^0 and 60^0 the deformation in the section became more uniform

- the extrusion load increases with an increasing semi-angle in the range

$0 \leq \alpha \leq 30^{\circ}$;

-the billet effective strain increases with an increasing extrusion ratio, *R*;

- by increasing the die land diameter from 12 mm to 20 mm (decreasing the reduction of area) the extrusion load decrease.

An overall concluding remark is that the FEA has proved to be useful for the investigation of the nature of the metal flow in forward hot superalloy extrusion.

The material flow is influenced by local friction conditions and die geometric shape. These aspects influenced the size of the dead zone in the material. In order to limit the friction force, die and ram has to be designed with appropriate dimensions.

In a future research, the authors intend to verify the model presented in this paper by comparing the numerical results with experimental measurements obtained under equivalent extrusion conditions.

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