Stress analysis of forward aluminium extrusion process using finite element method

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This paper presents the influence of stresses on the nature of the forward extrusion behaviour of aluminium alloy Al-2014, using different die angles (α=15°, 30°, 90°), and different die bearing length (4, 6, 10 mm). These stresses became high effect towards the die life. It was observed that the high values were created in the contact area between the die and the extruded material. The results showed that, a small die angles required higher extrusion load with 20% more than that of large die angles. In all used die geometry, the deformation of aluminium billet, which is caused by shearing and compression stresses, occurred in a small sectional area (bearing area). The results also showed that, the values of these stresses can either increase or decrease depending on the die entrance angle and the die bearing length. To avoid the effects of these stresses on die dimensions, the hardness, material selection, and geometry should be well calculated. A correlation between the calculated data and FEA was studied in this research by constructing an axisymmetrical 2D geometric (Al) model of the tooling and billet for analysis purpose. The required data, which include: effective stress, strain, material deformation velocity and die-work piece contact pressure were obtained from the finite element (FE) model.

Keywords: Stresses, Aluminium, Aluminium alloy (Al-2014), Extrusion, Process, Dies angles, Billet, Analysis, Finite element analysis

Introduction

Aluminium extrusion process

For many design applications, which require excellent versatility from a cross-sectional area, we find that the aluminium is an ideal material, because it can extrude to any shape. The high strength-to-weight ratio of aluminium and its alloys also makes it better than other materials, such as zinc. Aluminium properties and its versatility as a metal are accomplished by extrusion process. At present, the use of computer aided design in the manufacturing process gives more accuracy, improves tolerance, reduces design time and controls each stage of the process.[1] Nowadays, Finite element method (FEM) is one of widely used means for the analysis of many manufacturing process such as aluminium extrusion, as well as other forming processes. Both two and three dimensional aspects of extrusion can be investigated with this valuable tool.

During the extrusion process, the billet gets shorter and the friction surface between the billet surface and container decreases. Therefore, the necessary ram force decreases during the process. The die is also preheated before loading the first billet. A previous study has shown that many factors greatly influence metal flow in forward extrusion, such as the interface behaviour between the die and billet, distribution of thermal stresses along the contact area, and finally the die geometry.[2]

In addition, the influence of reduction ratio and die half-angle on extrusion was been studies for the hydrostatic extrusion process and can be utilised for the forward conventional extrusion process.[3]

Some mechanical characteristics of the extruded material will be change during the extrusion process, like the strain hardening.[4] Many FE solution methods were presented by researchers using ABAQUS software. By these solutions, they try to estimate the optimum die design and the relationship between the forward extrusion pressure and the die radius. Other studies try to combined tools of physical modelling technique and F.E simulations through studied the material flow behaviour over a conical punch. By using ABAQUS, the optimum die angle for conical die can be determined.[5]

In cold extrusion the radii of curvature of this extruded alloys and the average hardness along the product was to be increase with the increasing of the die length.[6]

Modelling, simulation and analysis method

Modelling of process

Modelling the parts can be done by different ways. The modelled parts can be imported from CATIA software. In this study, die, billet and billet container modelled as 3D, and in all cases the billet is modelled as deformable

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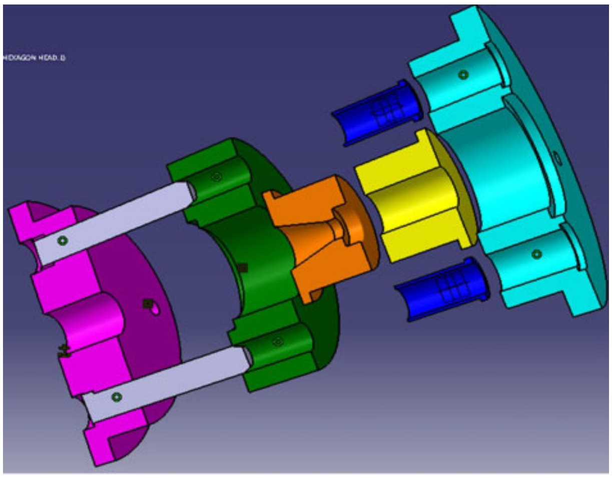
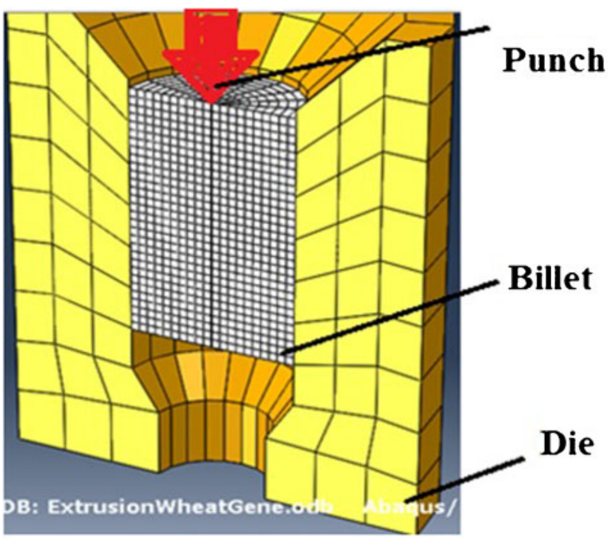


1 Cross-sectional view of assembly die

part, as shown in Fig. 1. Where the model consists of three main parts: rigid die, rigid billet container, deformable billet. In analyses and simulation process by ABAQUS, the parts modelled as 2D axisymmetrical geometric.

To investigate the simulation and analysis purpose of extrusion proses by ABQUS, an accurate two dimensional design was built with accurate dimensions and tolerances. Material and material properties was defined and assigned to these parts. All required steps like the model mesh, a properly boundary conditions was selected. Also optimisation process for this analysis was done by re-meshing the model much time to fine the elements and get accurate results. During the simulation, re-meshing facility was triggered to help the analysis of large de-formations. The meshed parts are shown in Fig. 2.

The chemical composition of the billets (initial diameter of 40 mm and height of 75 mm) are shown in Table 1. To remove the residual stresses from the billet before the extrusion, a preheat treatment process must be done. This process were achieved as several steps, including heating the aluminium billet in an induction oven to about 150°C, for ~15 min, then leaving it cooling to a room temperature gradually.



2 Finite element model of extrusion process

Table 1 Chemical composition (wt-%) of aluminium billet alloy (Al-2014)

Element	(Al-2014)/wt-%
Al	Reminder
Si	0·5–1·2
Mg	0·2–0·8
Cu	3·5–5
Ni	…
Sn	…
Mn	0·4–0·2
Fe	0·7
Zn	0·25
Cr	0·1
Ti	0·15
Other elements	0·2

The billet was made of aluminium and modelled as a von Mises elastic–plastic material with isotropic hardening. The Young's modulus is 38 GPa. The initial yield stress is 27 MPa. The Poisson's ratio is 0·33 and the density is 2·695 kg m^{-3}.

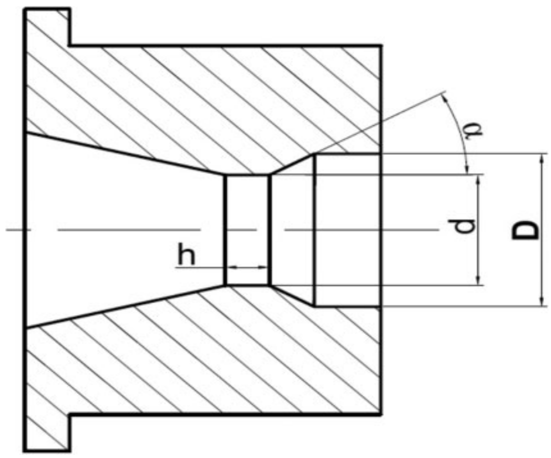
The theory of the FE analysis of the extrusion process is presented, with the detail description of analysis step, interaction, boundary condition and meshing.

Analysis step

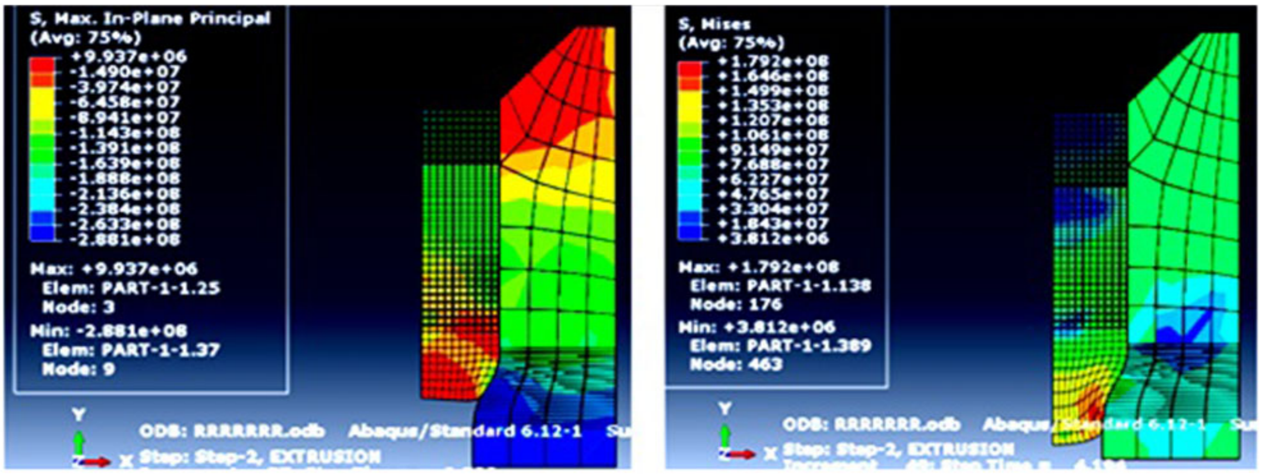
There are many types of interaction process between the parts, and a lot of factors will effects on metal flow and the resulting properties, such as billet length, container surface, extrusion ratio and extrusion speed. Also the actual die configuration, the section and its surface finish, the condition and shape of the bearing surfaces over which the aluminium flows and the die temperature also contribute.

In this study, we used a unique method such that the section is cooled and handled after leaving the die. With this method, it can be seen that a process, described as being like 'squeezing toothpaste from a tube', controlled a quite complex set of parameters.

Many times, during simulation, we need to change or modify the boundary condition or the load on the model. This modification is available by choosing the proper analysis step, which enable the designer to justify and define the interactions between the model parts, also its help for adding or removing any part. This analysis illustrates how extrusion problems can be simulated with ABAQUS. The radius of an aluminium cylindrical bar is



3 Die geometry



4 Stress distribution between inside die surface in radius bearing die

reduced 33% by an extrusion process. A simple meshing technique has been developed for extrusion problems as follows. The mechanism of extrusion starts when the applying force transmits from the external press to the active die through the transducer and pressure plate. Eliminating any force in the horizontal direction is important; by arranging the contact surface between the pressure plate and the force transducer in a suitable manner. Force F. was calculated using a modified upper bound equation[8]

$$F=2k_f*\left[4\mu*(H/D+h/d)+\mu/\sin\alpha+1)*\ln\left(D2/d^2\right)\right] \quad (1)$$

where D and d are the billet diameter and the die land diameter in (mm) respectively. H and h are the billet height and die land height in (mm) respectively. α is the die half angle (°), k_f is the maximum tangential stress at die/billet interface (N mm^{-2}), and μ is the coefficient of friction at die/billet interface, as shown Fig. 3.

A sequential solution in the present work, which based on operator splitting, was done by Eulerian formulation. Eulerian conservation equations in two steps used here[9]

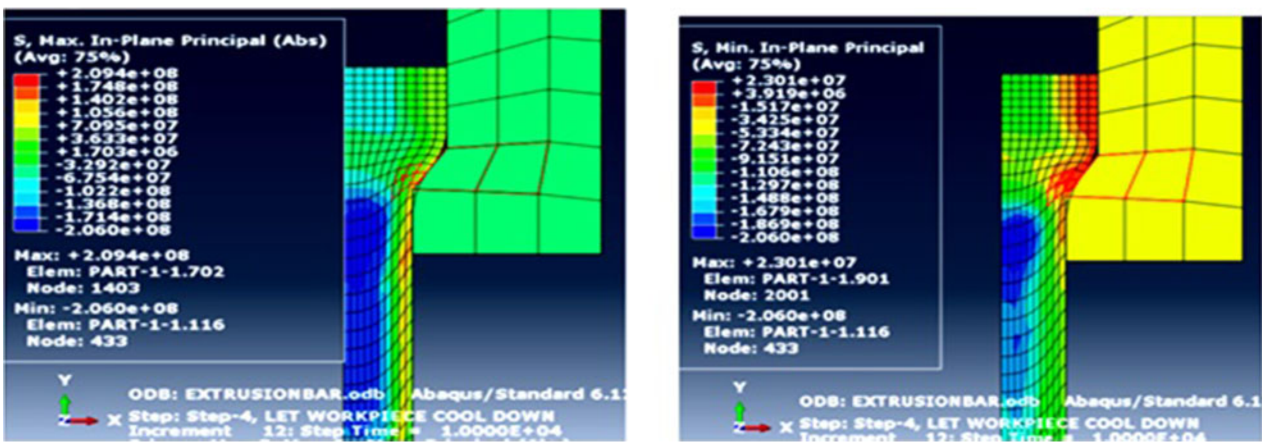
$$\partial\rho/\partial t+\nabla*(\rho u)=0$$
$$\rho(\partial u/\partial t)+\rho u*(\nabla*u)=\nabla*\sigma+\rho g \quad (2)$$
$$\rho[(\partial e/\partial t+u*(\nabla e)]=\sigma:\dot{\varepsilon},\ \text{where}:-\dot{\varepsilon}=\mathrm{D}\nabla*h+\rho r$$

where h is the heat flux, r is the internal heat source, and $D=\frac{1}{2}[\nabla u+(\nabla u)c]$ is the rate of deformation tensor. σ and˙ ε are the Cauchy stress and the strain rate tensor respectively. u and ρ are the velocity and density respectively. Von-Mises criterion used for accounting the material hardening and the non-linear behaviour of the billet material, also plotting stress–strain data are included.[9]

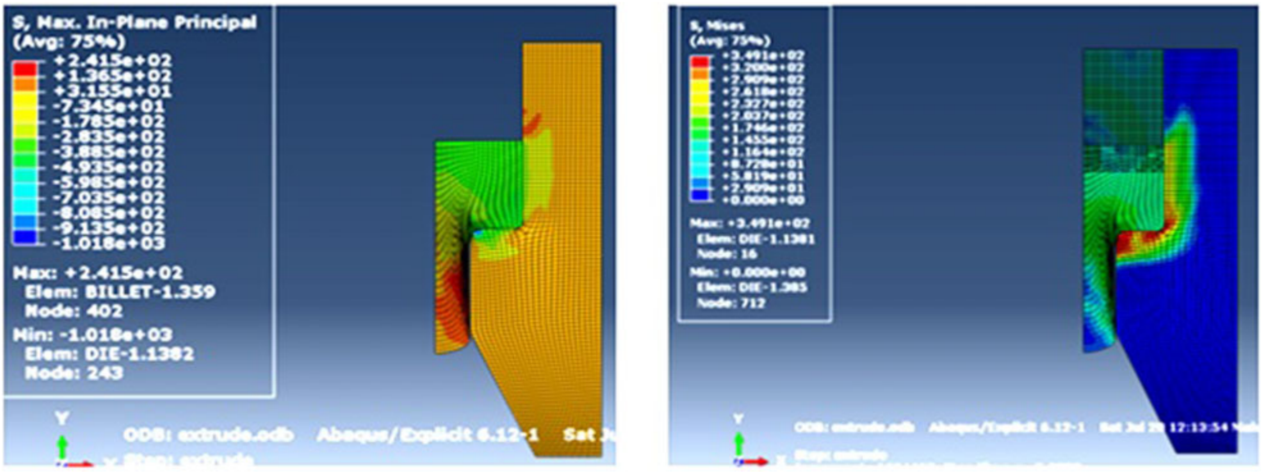
FEM simulation and stress distribution

The forward extrusion process of shapes sections has been investigated here using the FEM simulation. In all simulation steps, ABAQUS\Explicit software was used. As a result from this simulation, the stress distribution contour for the billet extrusion through a circular section die are illustrated in Figs. 4–6. In the first model shown in Fig. 4, where the die entrance section is curvature with angle 15°, it is obvious that the Von-Mises stress distribution is concentrate in centre of the section and flow towards the internal wall of work piece. Von-Mises stress diminishes in the external wall. Simulations results show that, the stress increases due to material flows under the punch and the billet container discontinuities.

In the model shown in Fig. 5, where the extrusion die angle is 30°, the direction of deformation stresses, which generated due the punch pressure, will concentrate in a conical shaped . In the last zone of the die, there is a



5 Stress distribution between inside die surfaces in a 30° die entrance angle



6 Stress distribution when die geometry is including radius with right angle

dead zone, which the aluminium stick on the die and acts rigidly like a part of it. Effective stresses will plotted easily after the FE simulations of (billet/die) interface contact pressure were done.

Figure 6 shows the result of the last extruded model. In this case, the die geometry included a radius with right angle. It can be seen from the results, that the stress distribution for this model was different from that of the previous two models. The maximum stress value in this model was determined to be 241·5 MPa. This high value of stresses occurs in the extrusion points, where the friction is the maximum. The high values of stresses are results of the interaction and interference between the billet and the die in bearing area, and dislocation of the particles was the direct reason. Extrusion stresses was plotted in high resolution form obtained from this FE simulation, as shown in the figure. As elucidated from the results, these types of extrusion required a force of 900 KN in average, especially when using a right angle die.

Results and discussion

The main stress distribution at various stages of the extrusion process on the billet is depicted in Fig. 7. In this figure the maximum stresses were observed for the case when the extrusion die angle is 90°, and the minimum stresses were found in the die that contains radius and extrusion angle is 15°. Also analysing was done to all output values from the finite element program, which includes material deformation, effective stress and strain, and extrusion force.

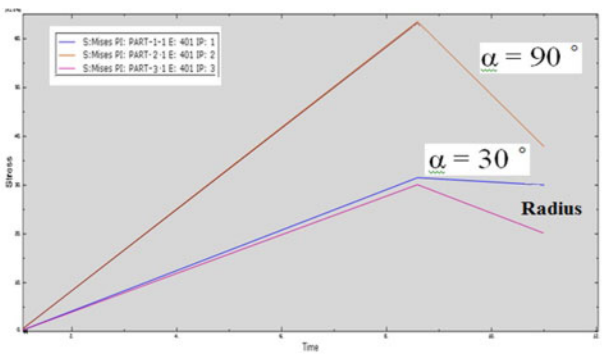
The major findings are listed as follows:

(i) the peak stresses occurs along the contact surface and in the region where the diameter of the work piece narrows down due to deformation

(ii) the plastic deformation locates near the surface of the work piece, where plastic strains are at the maximum

(iii) the peak temperature occurs at the surface of the work piece, as the result of plastic deformation and frictional heating, and immediately after the radial reduction zone of the die

(iv) the deflection of aluminium billet is determined by the modelling and simulating it as a deformable axis symmetry using the ABAQUS FE. The die is simulated as a rigid body. When the simulation reaches its steady state, the stresses at the interface between the die and the billet grows up and an updated Lagrangian simulation for the tool is performed.



7 Stress–time curve values for three models

Conclusion

1. Extrusion load increase with decreasing of die angle (α), since small die angle causes a dead metal zone.

2. Careful design of the extrusion dies profile can therefore control and reduce the stresses, which cause a main defect in product structure, that will support that it can be used to minimise the amount of in-homogeneity imparted in to the product, and therefore control the product quality.

3. The temperature of the extruded profile can be controlled as a constant throughout the whole extrusion cycle. The exit temperature is a measure of product quality.

4. Die specifications can be improved by controlling the finishing, hardness, tolerances, and material selected.

5. The ram speed and temperature should also be controlled, considering their significant impact on plastic properties of the billet material.

As a whole, this study demonstrates the main advantage of this type of extrusion. These advantages including the way to improve the mechanical properties of the workpiece.

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