# 3-D Numerical Simulation of Direct Aluminum Extrusion and Die Deformation

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## ABSTRACT

The design of extrusion dies depends on the experience of the designer. After the die has been manufactured, it is tested during an extrusion process and machined several times until it works properly. Therefore, the die is designed by a trial and error method which is an expensive process. In addition, after several runs the die may deform. This may lead to an unacceptable product. This paper focuses on 3-D simulation of a direct aluminum extrusion process. The behavior of the billet and die is predicted. In the simulation an Eulerian formulation is applied to simulate the flow of the material, rather than an Updated Lagragian formulation with remeshing. Finally, the results will illustrate how the die deforms and whether it deforms elastically or plastically and the influence of die deformation on the extruded product dimensions.

## INTRODUCTION

In a direct aluminum extrusion process the die is subjected to two types of loads: mechanical and thermal loads. These loads cause the die face to deform in a concave shape. Consequently, the section is extruded non uniformly through the deformed die where it is thinner at the middle and thicker at the edges [1]. Therefore, the dimensions of the extruded section may not be as specified.

Better understanding of the direct extrusion process including aluminum flow and die deformation requires 3D finite element simulations. But these simulations are faced with several problems that must be overcome such as model discretization, number of degrees of freedom, large deformation, calculation time, suitable material model and contact. The material flow can be simulated by Eulerian formulation to overcome large deformations. And the application of Updated Lagrangian formulation is sufficient to simulate the die because the maximum deformation is in the order of few millimeters.

The deformation of the die is influenced by two main factors: (i) the material flow which transfers the pressure or forces to the die, (ii) the parts that support the back of the die. The pressure distribution on the die can be determined by calculating the material flow through a rigid die. Consequently, the forces on the die can be determined. This method can be considered as a decoupled analysis which is illustrated in the following section.

In the current simulation the extrusion of a U shaped profile shown in figure 1 is studied. This actual example is taken from an aluminum extrusion company where the measurement of the die deformation may be conducted in the future. The die used in producing the above mentioned profile is supported in the extrusion direction with a backer and an insert as shown in figure 2. The fine cuts performed in the die that influence the material flow will increase the complexity of the die geometry. Moreover, the whole assembly including billet, die, backer and insert must be meshed at the same time in order to obtain a compatible mesh at the boundaries. The parts were modeled and discretized in SolidWorks and CosmosWorks respectively. CosmosWorks meshes either with linear or quadratic tetrahedron elements but quadratic elements are preferred in complex geometries. Therefore, quadratic tetrahedron element with 10 nodes is used in the discretization of the whole assembly. The finite element calculation is performed by the implicit finite element code “DiekA”. An isothermal finite element simulation is performed because only quadratic tetrahedron elements with three translational degrees of freedom per node are currently implemented in DiekA.

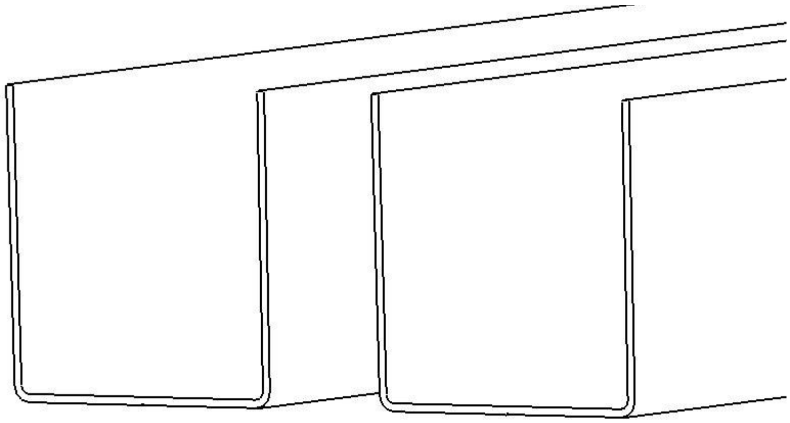

Figure 1: Extruded profile

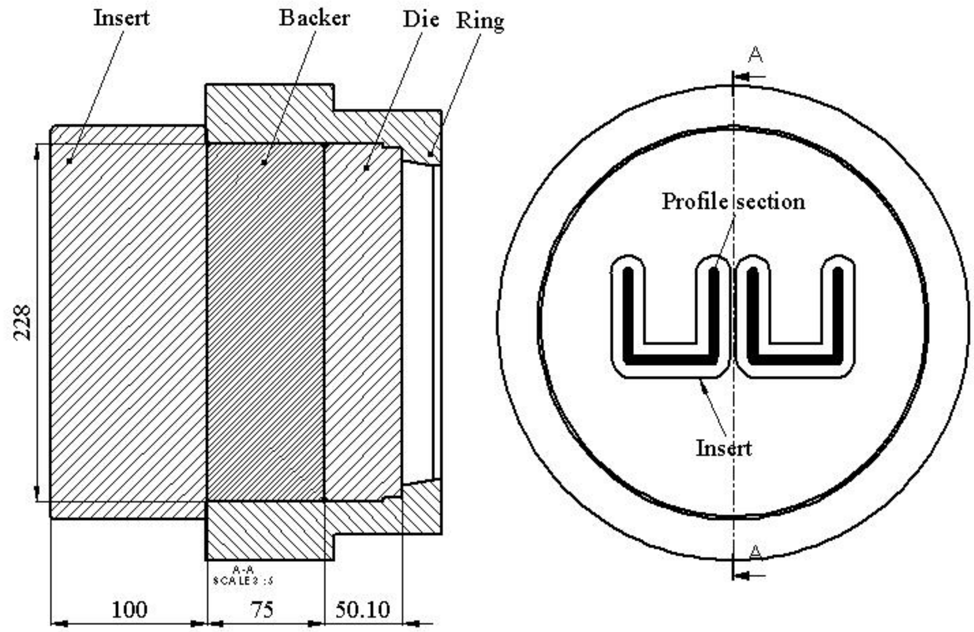

Figure 2: The die and its supporting parts (dimensions in mm)

## DECOUPLED ANALYSIS

The above mentioned profile is extruded by a 16 MN press. Therefore, the die is subjected to a force in the extrusion direction in an order of MN which leads to a high deformation in this direction. Then the parts that influence the deformation of the die in the extrusion direction can be considered in the current analysis. These parts include the aluminum, die, backer and insert. In order to decrease the complexity in predicting the die deformation by overcoming the large number of degrees of freedom and contact a decoupled analysis as illustrated in figure 3 is applied. In the decoupled analysis the aluminum flow and the die deformation are studied separately. First, a 3D isothermal numerical simulation for the billet is performed by applying an Eulerian formulation after the die has been filled. In this analysis a rigid die is assumed therefore a stick boundary condition is applied on the contact zone between die and billet. As soon as the analysis reaches the steady state, the reaction forces in the contact zone are calculated and transferred to the die face. Next a 3D isothermal numerical simulation for the die assembly is performed by applying Updated Lagrangian formulation.

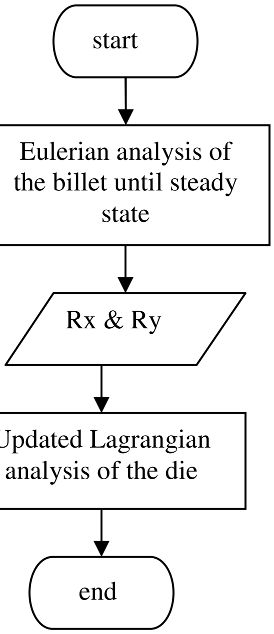

Figure 3: Schematic diagram for the decoupled analysis

## MATERIAL MODELS

The behaviour of aluminum alloy (AA6082) is described by von Mises viscoplastic material model. The relation between the flow stress and the equivalent viscoplastic strain rate is described by Sellars-Tegart law [2]. The material constants are listed in table 1.

$$\bar{\sigma} = \frac{1}{\alpha} \cdot \sinh^{-1}\left[ \left[ \frac{1}{A} \cdot \dot{\varepsilon} \cdot \exp\left( \frac{Q}{RT} \right) \right]^{\frac{1}{n}} \right]$$

Table 1: Constants used in Sellars-Tegart law

| n | Q (J/mol) | A ($s^{-1}$) | R (J/K.mol) | $\alpha$ ($MPa^{-1}$) | T (K) |
|---|---|---|---|---|---|
| 2.976 | 153000 | $2.39*10^8$ | 8.314 | 0.052 | 773 |

The tool material (AISIH-13 steel) is described by elasto-plastic material model in which Voce hardening is used to describe the plastic behavior. The material properties at temperatures of 25 and 500 $C^{\circ}$ are listed in table 2.

Table 2: Material properties of the tool steel at 25 and 500 $C^{\circ}$ [3]

| Part | Temperature ($C^{\circ}$) | Young's modulus ($N/mm^2$) | Yield stress ($N/mm^2$) | Poisson's ratio |
|---|---|---|---|---|
| Insert | 25 | 2.15E05 | 1150 | 0.29 |
| Die and Backer | 500 | 1.75E05 | 850 | 0.29 |

## BOUNDARY CONDITIONS

The following boundary conditions are applied to the billet's boundaries as shown in figure 4:

- Stick at cylinder-billet contact zone and die-billet contact zone
- Prescribed velocity of 10 mm/sec at the inflow.
- Free in the extrusion direction at the outflow.
- Average normal is applied at the bearing corner to decrease the number of degrees of freedom.

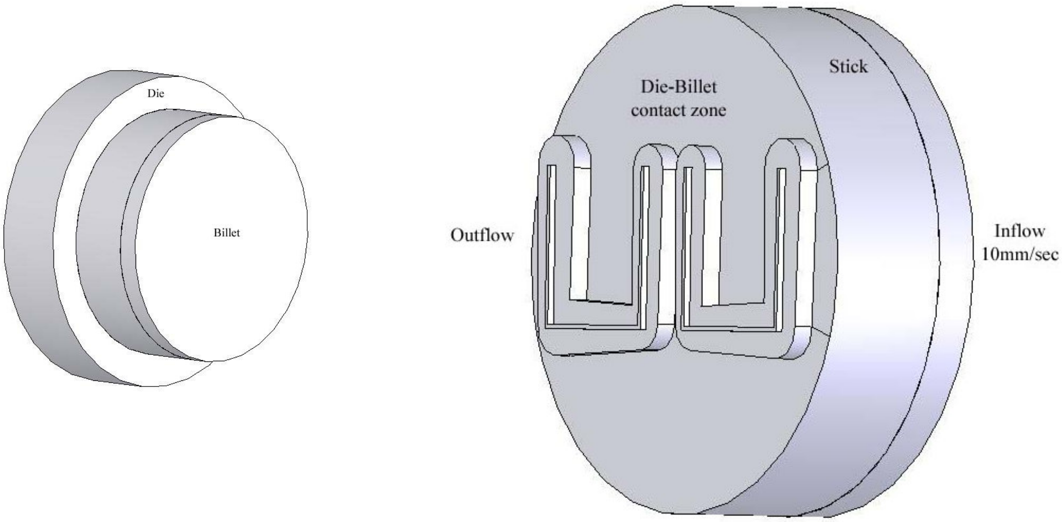

Figure 4: Billet’s boundaries

The following boundary conditions are applied to the die and its supporting parts:

- Suppress the contact area between the insert and the front plate in the extrusion direction as shown in figure 5.
- The influence of the ring on the die deformation is neglected.
- Forces are applied at the nodes belonging to die-billet contact zone.
- Connected degree of freedom of the contact nodes belonging to the three parts in the extrusion direction.

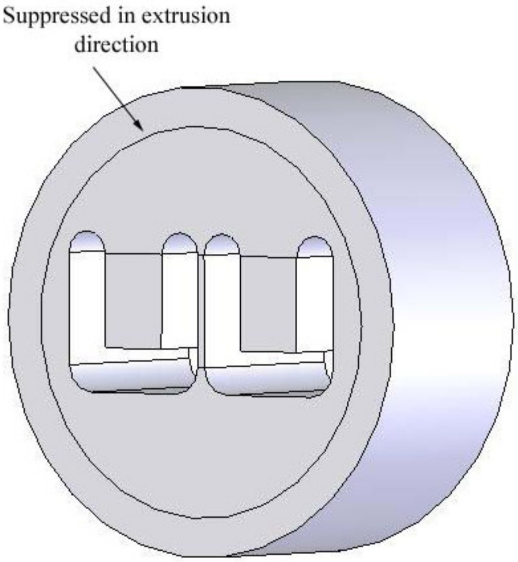

Figure 5: Boundary condition applied on the back of the insert

## BILLET AND DIE ASSEMBLY DISCRETIZATION

The model is discretized with quadratic tetrahedron element which represents the curved boundaries more accurately and produces better mathematical approximation in comparison with the linear tetrahedron element. The billet and die assembly are discretized by a 10 node tetrahedron element as shown in figure 6. Each node has three translational degrees of freedom. The total numbers of degrees of freedom for the billet and die assembly are approximately 300000 and 800000 respectively.

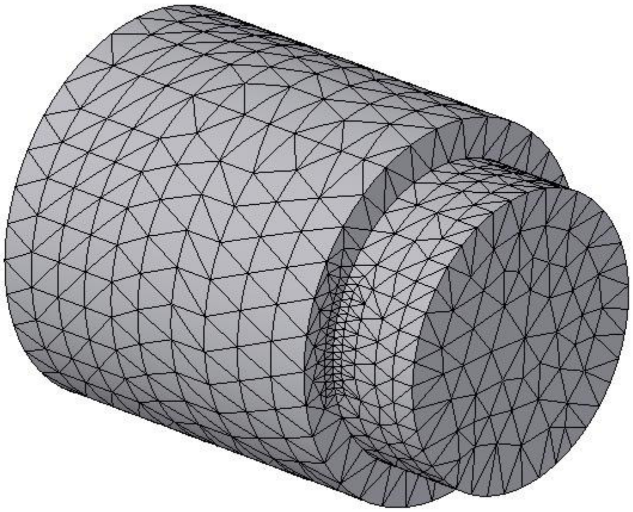

Figure 6: Discretization of the billet and die assembly

## RESULTS AND DISCUSSION

Figure 7 shows the deformation of the die in the z and y directions in order to draw up a better understanding of the die deformation. Figure 7 illustrates that the die is dished in because its deformation is decreased gradually from the center until its periphery. The maximum displacement reaches the value of 2.06 mm at the corner of the tongue. The relative displacement between the tongue and the middle of the die is about 1 mm. To check whether the deflection of the tongue under an extrusion force of 16 MN is reasonable, the deflection at the free end of a cantilever which is geometrically similar to the tongue is analytically calculated by the deflection formula of a cantilever found in mechanics of materials text books [4]. The deflection at the free end of the cantilever is about 0.7 mm.

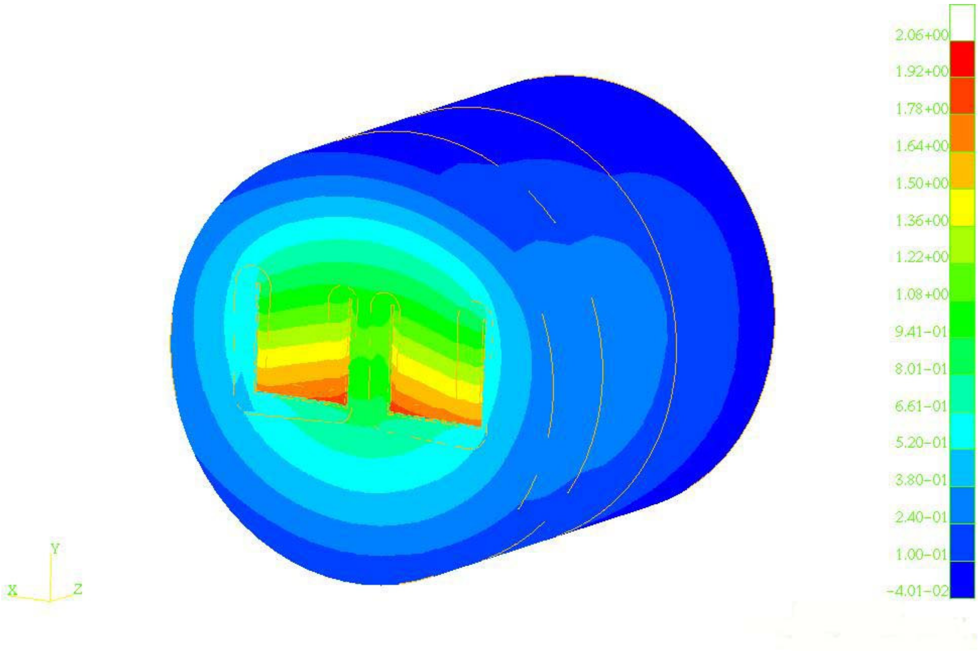

Figure 7: Displacement (mm) plot in z-direction for the die assembly

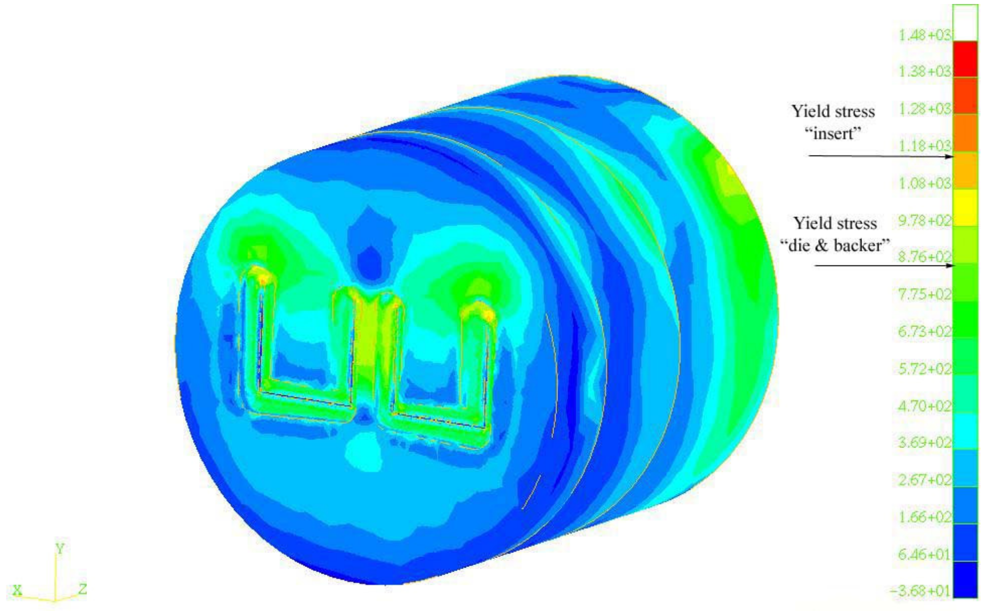

Figure 8: Von Mises stress (N/mm$^2$) plot of the die assembly

Figure 8 shows that in local regions of the die the stresses exceed the plastic limit especially at the joints connecting the tongue to the rest of the die. The value of the Von Mises stress at this region is reasonable because the bending stress at the fixed end of a cantilever reaches the value of 1800 N/mm$^2$.

## Conclusion and Future Work

The above analysis illustrates that the relative deflection between the tongue and the rest of the die reaches a value of 1 mm which may influence the geometry of the extruded profile. In addition, it shows that the die deforms plastically at local regions. The deformation and the stresses are overestimated because a rigid die is assumed with the aluminum flow calculation and an isothermal analysis is performed. These numerical results require validation through experiments which will be conducted in the coming period. In addition, a thermal analysis will be performed after the implementation of a quadratic thermal tetrahedron element in DiekA. Moreover, the decoupled analysis will be modified in order to increase its accuracy and robustness. Figure 9 shows the modifications that can be applied on the analysis such that the position of the billet's nodes belonging to the die-billet contact zone will be updated according to the deformation of the die until the aluminum flow reaches the steady state. By this modification on the decoupled analysis the influence of the die deformation on the extruded profile can be highlighted. Therefore, thermal and modified decoupled analysis will give better estimation for the deformation of the die and stress distribution in it.

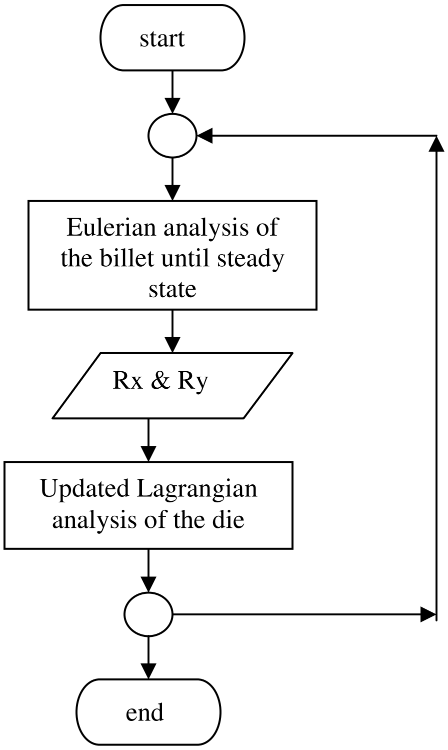

Figure 9: Flow chart concerning the modifications in the decouple analysis

## Acknowledgement

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