Effect of die pockets on the extruded products in Multi-hole Extrusion Process: A finite element simulation study.

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Abstract. Multi-hole extrusion process uses a die with more than one orifice through which the billet material is allowed to flow under compressive load. This process is suitable for obtaining many extruded parts of different shapes and sizes (automobile parts and components for medical devices) from a same billet material. The extrusion load, quality of the extruded parts depend on many process parameters like extrusion ratio, billet length, location of orifices or holes on the die, die land length, die design, lubrication and extrusion speed. During design of a multi-hole die, each hole shape and the profile of the hole are mainly considered. In that context, the die pockets play a major role in the extrusion process. The pockets of different geometry and shape are provided at the entry side of the die, through which the work material flows and subsequently pass through the die land region. The properly designed die pockets help in reducing extrusion load and produces parts with less variation in length. In the present finite element study, 2-hole, 3-hole and 4-hole dies have been used to extrude a billet material of 20 mm length and 20 mm diameter at an extrusion speed of 1 mm/min. This low extrusion speed does not put any strain rate effect in the extrusion process. The FE package DEFORM 3D has been used for this study. The diameter of each hole is 3 mm and the pockets of diameter 6 mm and depths of 3, 4, 5, 6, 7 and 8 mm are used. The billet material of lead alloy is used for understanding the process in both simulation and experiments. The detailed study on the extruded product lengths, mean stress on the product and the effective strain are studied. From the study it is observed that optimum pocket geometry for a particular die provides least variation in the product length, mean stress (compressive) and an in-depth focus on the deformation behavior (effective strain study). The study will help in selecting an optimum die design for obtaining high productivity with better quality products.

1. Introduction
Extrusion process has gained its importance in the industrialization era for producing many metallic and non-metallic products of different dimensions. The extrusion machine tool and die design depends on the extrusion load requirement. The cross-section of the product to be produced, the quality and property of the extruded products largely depend on the die design. Multi-hole extrusion process is a process in which the die is having more than one hole to get many extruded products from a larger single billet. Multi-hole extrusion process also reduces the effective extrusion load which is quite
suitable for the use of low capacity press. There are many research work available on the design of die for single hole extrusion dies but limited works are available for the multi-hole die. The study on multi-hole die extrusion was started with the work of Dodeja and Johnson [1957]. They carried out multi-hole extrusion with four different materials: pure lead, tellurium lead, pure tin and super pure aluminum with the dies containing one, two, three and four holes arranged in different fashion. The extrusion load was found to be dependent on total reduction and the positions of the holes. The authors observed that the lubrication has significant effect on the flow speed through the holes of multi-hole dies. The potential advantage of lateral extrusion was studied by Johnson et al. [1958]. There is more area available on the side where orifices can be placed compared to limited area available at the ends. However, lateral extrusion is not popular in industry, may be due tooling related difficulties.

After a lull period of more than three decades, the study on multi-hole extrusion gained its popularity again with mathematical modeling and experimental study. The finite element simulation study has helped the researchers and the extrusion industries in eliminating the trial and error study for the proper multi-hole die design. By this time, it was also felt about the usability of this process for producing small dimension products (micro metallic components). The upper bound method and finite element method have been used to study the multi-hole extrusion process [Keife, 1993; Ulysse and Johnson, 1998; Li et al., 2003a and 2003b; Peng and Sheppard, 2004; Peng and Sheppard, 2005 and Chen et al., 2008]. Most of these research papers explain the effect of different process parameters on extrusion load, exit velocity of the extruded products and quality of the product profiles. The control of the material flow through the die holes in a multi-hole die is quite complex and depends on the location of the holes, hole profiles, die land length, die pockets and lubrication conditions etc. The controlled material flow can be obtained by using a shaped pocket in front of the die. Li et al. [2003a, 2003b] studied the influence of pocket design parameter on metal flow by finite element simulations of two-hole extrusion and observed that pocket angle plays an important role in influencing the metal flow velocity and the pocket volume was found to be less effective in controlling the velocity of metal flow. The conical pockets were found to be most effective in increasing the flow velocity compared to the stepped pockets. Peng and Sheppard [2005] carried out the three-dimensional FEM simulation FORGE3® on the influences of the die pocket and offset of the pocket on the material flow and the structure. They observed that the balanced material flow and temperature distribution can be achieved by suitably located die pockets. Fang et al. (2009) studied the die pocket effect in the two hole extrusion of U-shaped aluminum profiles and observed the distortion and bending of the profile due to the differences in flow velocity. Das and Dixit (2011) studied the effect of die pockets in multi-hole extrusion process both experimentally and using FEM modeling to find out the variation in the product lengths. Das et al. (2014) studied the effect of locations and die pockets on the extrusion load in multi-hole extrusion process. From the literature, it has been observed that die pocket design in a multi-hole extrusion process plays an important role in change in extrusion load, product quality and the effective stress and strain. However, the design criteria for die pockets are not well established. In the present study, a kind of die pocket design has been considered and extrusion loads, product length variation, mean compressive stress of the billet in the pocket and the effective strain of the extruded products are studied.

2. Finite Element Simulation

Perhaps the most versatile of the computer-based analysis methods is the finite-element method. The finite element method (FEM) was originated in the field of structural analysis. It has been rapidly expanding to a wider range of non-structural problems for which exact solutions cannot be found with the traditional techniques. The models are considered to be two dimensional (plane strain) or three dimensional. Predominantly, finite element analysis of metal-forming problems involves large strain and inclusion of both material and geometric nonlinearities. The finite element method is expected to be used for simulating metal forming processes, because realistic boundary conditions and material properties can be taken into account. The combination of computer aided design packages and the finite element analysis is able to solve more complex problems in metal forming. A number of researchers
have employed finite element method for analyzing extrusion problems. For the present study the multi-hole dies (2-hole, 3-hole and 4-hole dies are used with different die pocket depths. The holes are located on the die at a pitch circle of 10 mm. The pocket diameter is 6 mm and kept constant for all simulation work. The billet material of dimension 20 mm diameter and 20 mm height is used for all simulations. The extruded product diameter is of 3 mm. Die pocket depths of 3, 4, 5, 6, 7 and 8 mm are used for all 2-holes, 3-holes and 4-holes dies. The schematics of some of the pockets in the multi-hole dies are shown in Figure 1.

![Figure 1: Schematic of the die pockets of multi-hole dies.](image)

For the finite element simulation, DEFORM 3D V6.1 has been used. The die, container and punch are considered as non-deformable and the workpiece material is considered as perfectly rigid plastic material. The workpiece material which is lead alloy was selected from the material library of the package. This is because the commercially available lead alloy has been used for experimental study also. The relevant properties of the available lead alloy and the material properties of the lead from material library closely match with each other. The (.stl) files of the models from CATIA are transferred to the DEFORM 3D pre-processor. The work material is meshed with tetrahedral elements of meshing size of 15000. The shear friction condition is taken as 0.3. The ram speed has been taken as 1.2 mm/min so as to avoid straining effect due to the strain rate. The extrusion has been carried out till the half reduction of height of the billet. The extrusion load is measured at steady state condition of the process. The mean stress (which is compressive) has been studied for the pocket region. The effective strain of the extruded parts are studied for obtaining the in depth information about the deformation behavior. This also provides information about the quality of the extruded products. The coefficient of variation of the extruded product lengths has been analyzed.

3. Result and discussion

Multi-hole extrusion is a complex process in order to understand the behavior of material flow and quite difficult to establish any concrete relationship between the different process parameters with the outputs
like extrusion load and product lengths etc. The die pockets play very significant role in balancing the material flow in the different holes located at different position of the die. In this study the extrusion load, mean stress, effective strain and the coefficient of variation of the product lengths have been studied.

3.1 Extrusion load
The determination of extrusion load is important for selection of the extrusion tooling and the press capacity. The least extrusion is always preferred for a better process. With simulation, the extrusion load is determined for the different multi-hole dies having different pocket depths. Table 1 shows the extrusion load for dies with different pocket depths. It is observed that the increase in number of hole on the die helps in reduction of the extrusion load. This is due to the decrease in extrusion ratio. In the earlier study it has been observed that the extrusion load is highest for the dies without any pockets. As the pockets are made at the entry side of the die holes, first the work materials flows into the pocket region, gets filled up and then starts flowing into the left out die land region.

| Die pocket depth (mm) | 2-hole die (kN) | 3-hole die (kN) | 4-hole die (kN) |
|-----------------------|----------------|----------------|----------------|
| 3                     | 13.2           | 11.8           | 12.0           |
| 4                     | 13.3           | 11.7           | 11.2           |
| 5                     | 13.5           | 12.2           | 11.1           |
| 6                     | 13.57          | 11.1           | 11.1           |
| 7                     | 13.47          | 11.9           | 11.13          |
| 8                     | 14.4           | 13.23          | 12.8           |

In the die land region again the ironing effect helps in further hardening of the extruded products. It is quite interesting to observe that with the increase in the pocket depth, the die land height decreases which must help in reduction in extrusion load. From the above table it can be observed that with increase in the die pocket depth from 6 mm to 7 and 8 mm the extrusion load starts increasing. This may be due to the excess compressive load required for the secondary extrusion like situation in the pocket region. The sufficiently large amount of materials get deposited in the pocket region and needs more load to get deform further and to start flowing through the die land region. For die pocket depth of 3 mm, a small increase in of load for 4-hole die (1.7%) as compared to 3-hole die. This may be due to inconsistency in the error compensation in steps of steady loading.

It is evident that a particular configuration of die holes need a proper design of pocket (based on the depth and diameter mainly) in order to have a lesser extrusion load. In the case of 4-hole die a more consistent extrusion load condition is observed. The more number of holes gives rise to low extrusion ratio and the effect of pockets gets less affected.

3.2. Mean stress
The study on the compressive stress on the material in the die pocket region explains the relative increase in the effective strain and also the increase in the cumulative extrusion load. Table 2 shows the compressive stress observed in the pocket region.

| Die pocket depth (mm) | 2-hole die (MPa) | 3-hole die (MPa) | 4-hole die (MPa) |
|-----------------------|------------------|------------------|------------------|
| 3                     | 23.0             | 18.1             | 19.93            |
| 4                     | 20.8             | 22.4             | 24.4             |
| 5                     | 20.8             | 20.03            | 21.2             |
| 6                     | 25.9             | 19.9             | 6.2              |
| 7                     | 25.9             | 22.2             | 26.1             |
3.3. Effective strain

Effective strain is the measure of the rate and amount of plastic deformation on the work material during the process. Higher effective strain indicates the greater amount of work on the extruded products. The higher value of the work material also is a measure of the mechanical quality of the product. Figure 2 Shows the effective strains obtained for the extruded products coming out from the different dies with different die pockets.

![Effective strain for the extruded products.](image)

For the case of 2-hole die a uneven trend of the effective strain is observed as compared to 3-hole and 4-hole dies. This may be due to the highly uneven material flow behavior through two hole die. The consistent in the effective strain is a healthy sign of the product quality in terms of strength but some relieve in the strain value is observed towards the end of the product (the free end after the die land region). Figure 3 show the effective strain distribution for 4-hole die with 4 mm pocket depth as an example case. In the case of 4-hole die, much variation in the effective strain for the extruded products is not observed. This indicates the ease of material flow for the die with more numbers of holes.
Figure 3. Picture of the effective strain in simulation

3.4. Product quality and length analysis
In the multi-hole extrusion process the unequal product length is a challenging issue for the researchers. Many attempts have been made to change different process parameters and die design to produce the more uniform products. In this work the extruded product lengths have been studied. The extruded products coming out from different dies with different die pockets are measured and the coefficient of variation is measured using the simple formula (Coefficient of variation= (standard deviation/average value) ∗ 100%). Table 3 show the coefficient of variation of the product lengths obtained from different dies.

Table 3. Coefficient of variation of the product lengths

| Die pocket depth (mm) | 2-hole die | 3-hole die | 4-hole die |
|-----------------------|------------|------------|------------|
| 3                     | 4.7        | 7.56       | 10.61      |
| 4                     | 1.55       | 6.54       | 3.58       |
| 5                     | 1.4        | 5.64       | 3.96       |
| 6                     | 4.65       | 6.52       | 3.24       |
| 7                     | 3.5        | 4.06       | 4.64       |
| 8                     | 4.12       | 4.33       | 4.15       |

From the table 3 it is observed that the variation in the extruded product length is more when die pocket depth is less i.e. 3 mm. A good consistency is observed with the variation in product length with increase in the pocket depth. It is expected that the variation should be as least as possible. However, in the present study, for the pocket depths 4, 5, 6, 7 and 8 mm, the variation in product length lies between 5-6 %. This is a good approach to reduce the variation in the product length by introducing the die pockets. The combined effect of location of the holes in the die and the selection of die pockets may further help in reducing the variation in the product length.

Whenever the quality of the extruded products is considered, the mechanical properties are more prominent to the application of the products. But the profile of the extruded products cannot be ignored. In the present study it has been observed that the products get bend while coming out from the higher die pocket depths. It is quite apparent that the die land length helps in producing more straight products than the die pockets. Figure 4 shows a comparison of the extruded product profiles coming out from a 4-hole die

4. Conclusion
In the present study the effect of die pockets in the multi-hole die on different process outputs are studied. The extrusion load found to increase with increase in the die pocket depth after a certain value.
The mean stresses which are compressive was studied for the material in the pocket zone also show the increase trend with increase of pocket depth and this also contribute to increase in the extrusion load. The effective strain shows the quality of the extruded products. The die pockets helps in reducing the variation in the product length. However the bending tendency also increases with increase in the depth of the die pockets and for this situation the die land length plays an important role in production of straight products.

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