Experimental and finite element analysis study of die geometrical affect the forming load during extrusion process

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Abstract. The effect of extrusion parameters on the extrusion of Al1100 pure aluminum was investigated with the aid of numerical methods. With this regard, the process parameters, three die angles (15°, 30°, 45°), and three forming velocities (1, 2, 3 mm/min) were studied. Besides, the experimental results were analyzed using the finite element analysis (FEA) using ANSYS 16. All the experimental and numerical results were compared to each other and it was concluded from the results that the effect of die geometry on the forming load is more dominant than forming velocity. In addition, it was observed that the increase in the extrusion speed causes a significant increase in the forming load for all die angles.

1. Introduction
Extrusion is a metal forming process that is widely used in industry and daily life equipment. It is another kind of manufacturing process which involves shearing and compression [1]. The practical application of extrusion includes railing for sliding doors, tubing having various cross-sections, structural and architectural shapes, and door and window frames. Extruded products can be cut into desired lengths, which then become discrete parts such as brackets, gears, and coat hangers. It is a process in which the product can be formed by using a semi-conical die or any taper-shaped die. A round billet is placed in a chamber and forced through a die opening by a hydraulically driven ram or pressing stem. This process usually comprises of axisymmetric die [2,3]. The forming load influenced by many extrusion parameters but the die angle and ram velocity have the greatest effect on forming load, thereby the feature of extruded parts.

W. Schmidt and R. Naik [4] built finite element models to study metals’ behavior during the extrusion process. The effect of the shape of the die, reduction ratio, and the friction occurred on the flow characteristics during the extrusion process were studied. To study the effect of the geometrical shape of the die on the quality of extruded parts, four types of the die shape (elliptic, cosine, conical, and hyperbolic) were used. Numerical results include Stress and strain rate distributions produced in the extruded parts together with pressure and velocity fields were analyzed.

Stress analysis of axisymmetric aluminum Al-2014 extrusion process presented by H. M. Magid et al. [5]. The influence of geometrical die on effective stresses and strains and deformation of Al billet were obtained in this study from the FEM. Three die angles and three lengths of die bearing were used. The results showed that a decrease in the extrusion load with increased die angles, and the shearing and compression stresses produced the deformation of Aluminum billet occurred in a small bearing area of the die.

O. Ayer [6] discussed the investigation of some factors on the forming load required of the extrusion process of AZ31 Magnesium experimentally and numerically. The temperature, friction, speed of punch, and reduction ratio were the parameters that studied experimentally. It was concluded...
increase in the friction factor and punch speed would increase the extrusion load largely. Also, higher reduction ratios required higher extrusion temperatures to reduce the forming load.

The effect of forming speed and the coefficient of heat transfer occurred between tool and billet on the forming load and temperature distributions on the extruded products investigated by M. O. Gortan [7]. It was noted from the results obtained experimentally and numerically the speed forming has a significant effect on the temperature distributions on the workpieces, while as heat transfer coefficient didn’t have a clear effect on the process force.

Y. Dewand et al. [8] presented a brief review of the contributions made by previous researchers in the field of the extrusion process, it is found that researchers used Al alloy and steel alloy for extrusion as workpiece materials in most of the cases. Also, they investigated the effect of some parameters process on the punch force-punch stroke results for different conditions. the result from these conditions was compared with results obtained by the finite element program, ABAQUS code.

HyperXtrude metal [9] software based on the FEM was utilized to simulate and analyze the extrusion process of a standard structure box profile of AA6063 Al alloy by using porthole die introduced by S. Bingol et al. [9]. In this study, the investigation of the main parameters of the process on the product quality and dimensional accuracy was studied. The result displays that the quality of product and dimensional accuracy will be satisfactory after evaluating the results of the numerical study.

D. Luca [10] carried out simulations of a cold extrusion process using FEM. The stresses, strains, and temperature distributions on the extruded product material were analyzed. Various die angles used to investigate the effect of them on the material flow, extrusion load, and die life. It is noted the extrusion load varies directly with die angle. Experiments were carried out to validate the FEM results. The result showed a good agreement between these data.

Experimental evaluation and FEM presented by R. K. Sahu and R. Das [11] of the backward, forward, and multi-hole extrusion process to determine the forming load and lengths of products. It is concluded, the forming load varies depending on punch speed, friction conditions, and the ironing effect, while the lengths of extruded products vary depending on die land lengths. As well as, they used two types of die (5- hole, 9- hole) dies, they concluded the difference in the material flow behavior through these dies would lead to producing a change in the product length.

In this study, the effect of die geometry and extrusion velocity on the forming load experimentally and numerically were discussed. Ansys 16 based on FEM is used to simulate and analysis the extrusion process.

2. Fundamental definition

Figure 1 will be as a reference in discussing some of the parameters in extrusion. The diagram assumes that both billet and extrudate are round in cross-section. One important parameter is the extrusion ratio, also called the reduction ratio [1]. The ratio is defined:

\[ r_e = \frac{A_o}{A_f} \]  

where

- \( r_e \) = extrusion ratio.
- \( A_o \) = cross-sectional area of the starting billet.
- \( A_f \) = final cross-sectional area of the extruded section.

The value of \( r_e \) can be used to determine true strain in extrusion, given that ideal deformation occurs with no friction and no redundant work [4].

\[ \varepsilon = \ln(r_e) = \ln\left(\frac{A_o}{A_f}\right) \]  

Under the assumption of ideal deformation (no friction and no redundant work), the pressure applied by the ram to compress the billet through the die opening depicted in the mentioned figure can be computed as follows:
Where
\[ p = \bar{\bar{f}} \ln(r_x) \]  \hspace{1cm} (3)

\( \bar{\bar{f}} \) = average flow stress of work billet material during deformation.

3. Numerical Simulation

The major purpose of numerical simulation is to check the validity of the proposed extrusion angle accompanied by ram speed, while the minor purpose was comparing the outputs of experimental work with the results of the simulation.

In ANSYS Workbench the model geometry was created in the design modeler. Two-dimensional axisymmetric model was built due to loading and geometry symmetry conditions, the model consists of die and billet where a specific constraint was applied instead of die container and press ram as presented in figure 2. The numerical model should deal with two types of nonlinearities the first is material nonlinearity that comes from nonlinear relationship of stress-strain curves for aluminum as introduced in section 4, the other type is geometry nonlinearity, where this type arises as a result of large deformation and change in shape of work billet.

Augmented Lagrange formulation accompanied with the Coulomb friction model was used to define the contact interface between die and billet with a friction coefficient of 0.15 as a result of dry extrusion. The element type for billet was PLANE183. The elements in the contact interface were CONTA172 for contact side and TARGE169 for target side. Based on the output of the numerical model the appropriate conditions (die angles and forming velocities) were used in practical tests.

Figure 1. Basic of the extrusion process.

Figure 2. The constraints applied to the numerical model.
4. Experimental work

1100 aluminum alloy was used to prepare work billet with 50 mm length and 25 mm diameter. The tensile test was carried out to determine the mechanical properties of this material, figure 3 presents the stress-strain curve while table 1 shows the values of mechanical properties obtained from the tensile test, the chemical composition of work billet material presented in table 2. The dies are designed in accordance with K. Geethalkshmi [12]. Container and die are made integral. Three dies were manufactured with angles (15°, 30°, 45°) and extrusion ratio 1.66. The die is made of tool steel. The die is heat treated to increase hardness and finished.

![Stress-strain curve](image_url)

**Figure 3.** Stress-strain of aluminum 1100.

| Material property | Modulus of elasticity (E) | Poisson's ratio (ν) | Yield stress (σ_y) |
|-------------------|---------------------------|---------------------|--------------------|
| Magnitude         | 75 GPa                    | 0.33                | 110 MPa            |

**Table 1.** Mechanical properties of billet material Al A1100.

| Component | Cu  | Si  | Mn  | Fe  | Zn  | Al  |
|-----------|-----|-----|-----|-----|-----|-----|
| Percentage | 0.08 | 0.61 | 0.02 | 0.048 | 0.042 | 99.2 |

**Table 2.** Chemical composition of work billet material Al A1100.

Extrusion experiments are carried out to achieve a reduction in diameter from 25 mm to 15 mm by mounted extrusion die on the testing machine, the design extrusion die is present in figure 4 while figure 5 shows the complete extrusion tool that used in the experimental work. The testing machine type is (WDW-200E) has a capacity of (200KN). The extrusion force and stroke were directly measured on this testing machine. The mentioned reduction in billet diameter was performed experimentally by controlling two process parameters each one with three levels as shown in table 3.
Table 3. Process parameters in experimental tests.

| Process parameters | Extrusion velocity (mm/min) | Die angle (degree) |
|--------------------|-----------------------------|--------------------|
| 1                  | 15                          |                    |
| 2                  | 30                          |                    |
| 3                  | 45                          |                    |

Figure 4. Cross-section view of the extrusion die.

Figure 5. Isometric view and a photo of a complete extrusion die.

5. Results and discussion
Two parameters are studied to investigate their effect on extrusion of forming the required to produce a round billet with a certain reduction in cross-sectional area. More reliable extrusion products may be attained by giving more attention to selecting the best process parameters especially forming velocity and die angle.
5.1 *Effect of die angle on forming load*

It is found that load required to deform billet decreases significantly by decreasing die angle as presented in figures 6, 7 and 8, that resulting from increasing extrusion angle leads to improve metal flow, furthermore, the transient region between entry cross-section and output cross-section increased. The greatest forming load was 167 (kN) occurred when the die angle was 45° and ram speed was 3 mm/min. The lowest forming load was 88 (kN) occurred when the die angle was 15° and ram speed was 1 mm/min.

For 15° and 30° die angles, a contact area of the die is large, leading to increased friction at the die–billet interface. Higher friction results in larger ram force. On the other hand, a large die angle causes more turbulence in the metal flow during reduction, increasing the ram force required.

5.2 *Effect of ram speed on forming load*

Since the extrusion ratio is kept constant and as the ram speed increases the time available for the material to flow through the die decreases and that increasing the resistance of the metal, thereby the required forming load increases. For the 45° die angle, it was noted that the forming load increased by 9.7% and 6.3% that when ram speed increased from 1 to 2 mm/min and from 2 to 3 mm/min respectively. On the other hand, for the 15° die angle, the percentages of the increase in forming load were as follows 16% and 14.7% that when ram speed increased from 1 to 2 mm/min and from 2 to 3 mm/min respectively.

The two parameters (die angle and the extrusion velocity) which have been studied separately by many authors as mentioned in section 1, but the results of this research showed the great correlation between them. As a result of this interdependence selecting of die angle must depend on extrusion velocity and vice versa.

The sequence of extrusion in numerical modeling presents in figure 9, the figure also shows the successfully extruded parts in experimental work.

**Figure 6.** Effect of die angle on forming load (ram speed = 1mm/min).
Figure 7. Effect of die angle on forming load (ram speed = 2mm/min).

Figure 8. Effect of die angle on forming load (ram speed = 3mm/min).

Figure 9. The sequence of extrusion in numerical modeling and experimental tests.
6. Conclusions
1. The study has shown that it noted that generally, the forming load increases with increasing the die angle and ram speed.
2. Small die angles were more affected by increasing ram speed than large die angles.
3. The maximum forming load for all die angles occurs near the mid-travel of ram stroke.

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