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Extrusion die geometry effects on the energy absorbing properties and deformation response of 6063-type Al–Mg–Si aluminum alloy ☆

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ABSTRACT

The response of 6063-type Al–Mg–Si alloy to deformation via extrusion was studied using tool steel dies with 15°, 30°, 45°, 60° and 75° entry angles. Compressive loads were subjected to each sample using the AVERY DENISON machine, adapted to supply a compressive load on the punch. The ability of the extrudate to absorb energy before fracture was calculated by integrating numerically the polynomial relationship between the compressive stress and sample strains. Strain rate was calculated for each specimen and the deformation zone length was mathematically derived from the die geometry to decipher its influence on both lateral and axial deformations. Results showed that extruding with a 15° die was the fastest as a result of the low flow stress encountered. Outstanding compressive strength, plastic deformation, strain rate and energy absorbing capacity were observed for the alloy extruded with a 75° die angle. Increase in die angles led to a decrease in deformation zone length and samples deformed more in the axial direction than in the lateral except for the 45° die which showed the opposite; the sample also showed the least ductility.

1. Introduction

The outstanding properties of aluminum have led to their wide usage in the field of engineering [1,2]. As a result of this, different metal working processes such as rolling, forging, and extrusion, have been employed to obtain different desired shapes and properties. In metal forming processes, the flow stress of the metal is an important factor to consider for a successful operation [3,14–18]. This flow stress is a function of forming pressure and the deformation load. The stress is usually reduced with temperature; hence a high working temperature is beneficial to carry out the operation with a low load or pressure. Since extrusion involves the application of an external load on a material which forces it through wear resistant openings (die), the stresses induced in this metal (due to the application of external forces) are greater than its yield strength but less than its fracture strength [4,6]. Cold extrusion is majorly employed for the manufacture of special sections as the metal is made to flow under cold conditions (room temperature) and a high pressure; this imparts good mechanical properties and surface finish on the work piece [5]. Extruding a billet above the recrystallization temperature (hot extrusion) engenders pressure decrease along the container as the ram/punch advances and when the ram speed increases, a structure with no coarse grains occurs [6,7].

Investigations on die geometry effects and extrusion speed on aluminum and lead alloys have shown that average hardness and radii of curvature of these extruded materials along circumferential solid positions increase with loading rates and increase with decrease in die reduction in the area [8]. Using a die with a guiding angle eliminates shrinkage cavities of samples owing to the axial stress which changes from tensile to compressive in the central zone. Dead zone generation is reduced as the metal flow remarkably becomes homogenous [9]. Die angles are observed to eliminate surface cracks of the exit die as a result of the reduction of axial stresses at this zone. The initial stages of the deformation, where the billets are primarily affected by the flow stress of the material and the rates, at which the work is carried out, have proven to be of some significance in dictating the material flow distribution during the extrusion process [10].

The response of metals to deformation is key in the extrusion process because it affects the tool life; it determines product delivery rate and most importantly, the performance of products when used in engineering applications. Hence, in this study, the need to

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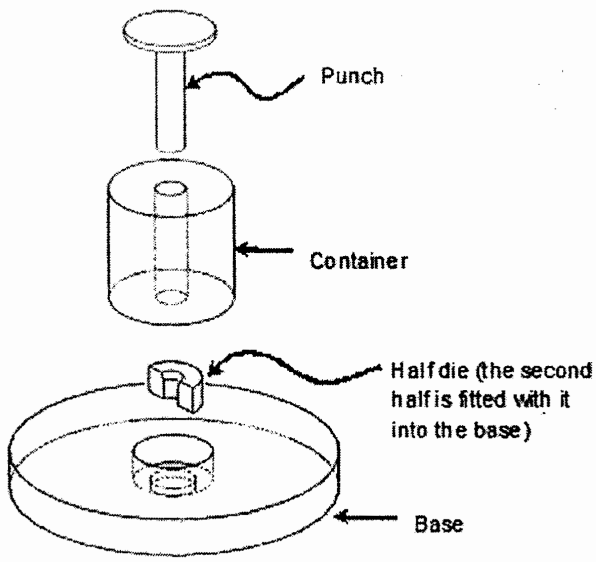

Fig. 1. The punch and the form tool set up.

decipher the dependence of alloys' plastic flowability (per time) and energy absorption properties on die geometry and deformation load was ascertained.

2. Experimental procedure

Mild steel, owing to its appreciable abundance and cheapness with a chemical composition of 99.2% Fe as the major constituent, was used in designing the punch and the form tool, comprising the cylindrical container and the base as shown in Fig. 1. These components were heated to a temperature of 850 °C and quenched in water for 10 min after holding for three hours in the furnace so as to increase their strength and hardness to suite the deformation process and prevent wear and deformation during extrusion. The extrusion dies used were made of tool steel and were designed such that five entry angles (15°, 30°, 45°, 60°, and 75°) were fabricated to produce cylindrical extrudates. Billets made of aluminum alloy (Al–Mg–Si type) were sand cast into cylindrical shapes and machined to a 25.1 mm diameter and 19 mm height for extrusion. The shaped aluminum components are extruded at room temperatures to obtain good surface finishes, better dimensional consistency and improved strengths. Each die was fitted into the form tool base and extrusion was carried out at room temperature with the AVERY DENISON machine, which was adapted to supply a compressive load on the punch. The extrusion load (in KN) applied on the ram was read on this machine while a gauge, attached to the machine, was used in determining the time deformation took place at each point in the die. As each load was applied, the pointer on the meter rotated and a complete rotation was taken for 1 mm punch displacement.

3. Results and discussion

3.1. Extrusion load against punch displacement curve

Fig. 2 shows the extrusion load – punch displacement relationship for different die angles. The curves for extrusions with 60° and 75° dies show that aluminum samples deformed in a similar mode though different loads were needed to deform these samples while the punch traveled at varying displacements. According to [11], the curves for these two dies have shown that a maximum degree of plastic deformation was achieved when 65° and 75° dies were used as compared with the rest (15°, 30° and 45°, respectively). Maximum extrusion pressure for each sample, which was obtained by dividing maximum load by sample's original area (shown in Fig. 3), reveals that the maximum pressure needed to deform the aluminum alloy increases with increasing die angles. Relating these relationships shows that how far a punch travels during extrusion is not wholly dependent on the magnitude of the maximum pressure – geometry of the die (especially the entry angle) but however, billet's inherent properties could induce such deformation conditions based on the hardenability of the material which is a function of energy tendency.

3.2. Sample displacement with time

The displacement versus time relationships at constant temperature shown in Fig. 4 does not only show the displacement of each alloy, it also shows the time (at each point) it takes in achieving

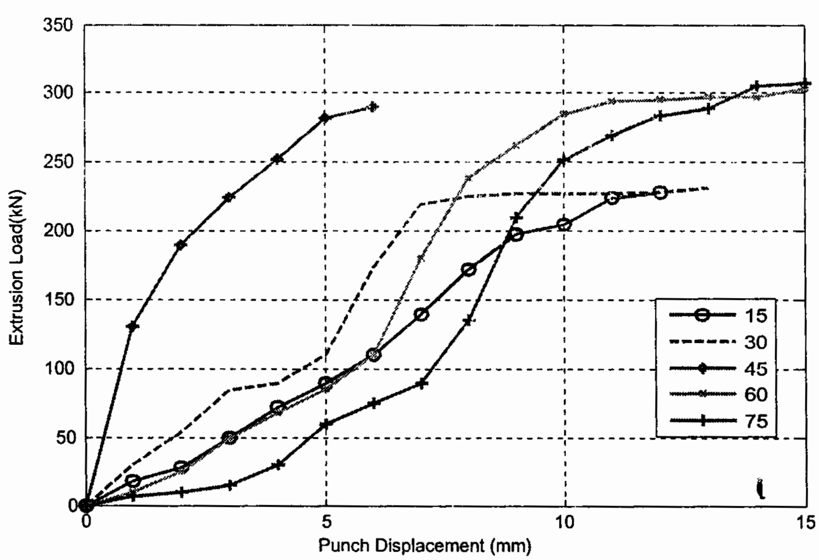

Fig. 2. Variation of extrusion load with punch displacement.

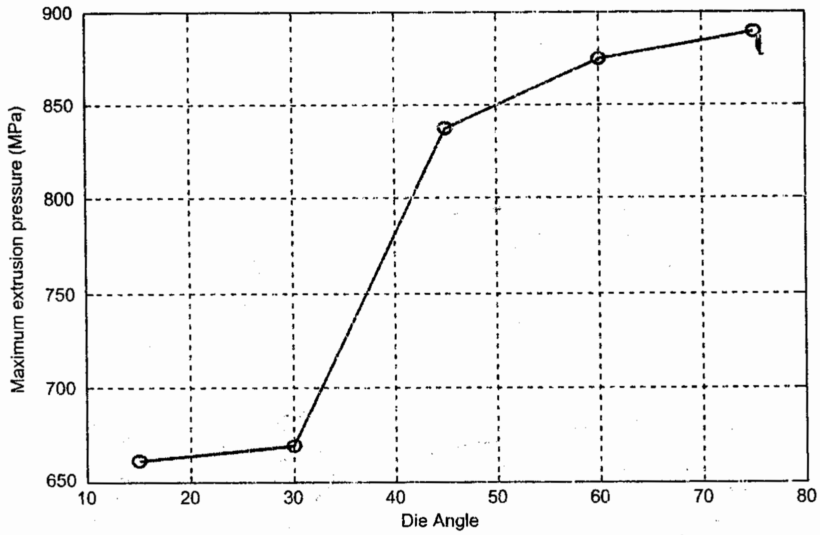

Fig. 3. Effect of maximum extrusion pressure against die angle.

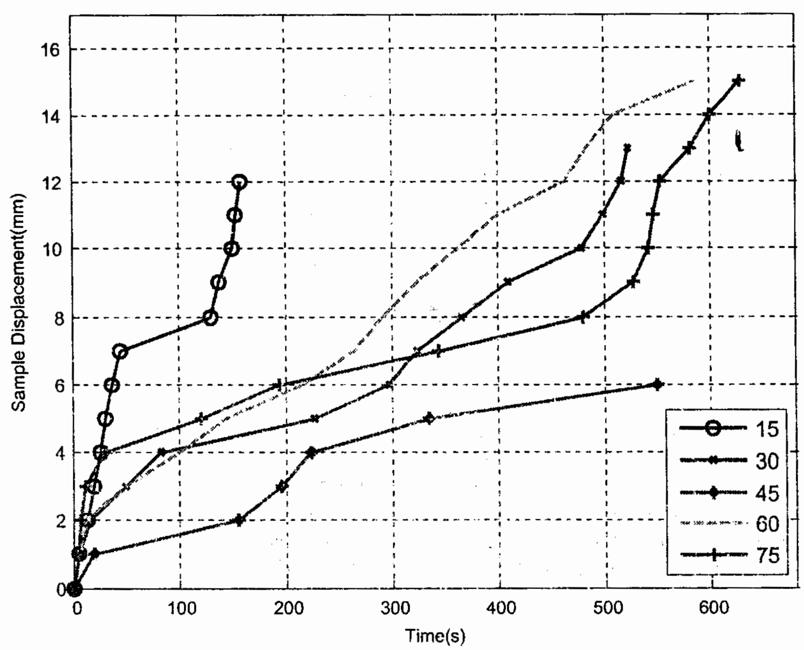

Fig. 4. Variation of sample displacement with time.

this. This gives an understanding of the ease with which each sample is deformed. As discussed in Figs. 2 and 3, more time (≈585 and 625 s) was needed for alloys to elongate to their final sizes (axially) with 60° and 75° dies, respectively. Using a 15° die, the best deformation ease was attained as 157 s was needed for a complete deformation. The longest process was discovered to take place using a 75° die though its deformation was the best. Deforming the alloy with a 45° die shows that it is possible for samples to cover a little displacement within a large space of time.

3.3. Energy absorbing property of extrudates

Results on extrusion pressures and corresponding sample strains for each entry angle were calculated and with the use of MATLAB, polynomial relationships between these two variables were computed. The energy (per unit volume) U, which is a measure of the tendency of the extrudates to absorb energy before failure during service, was calculated by integrating numerically using the expression [12,13].

$$U = \int_0^{\varepsilon} P d\varepsilon$$

where P and ε are the extrusion pressure and sample strain respectively. The capacity of samples to absorb energy before plastic deformation ceasure is moderately large (in increasing order) for extrusions with 15°, 30°, 60° and 75° die angles (Fig. 5). It is obvious that a 75° die gives the alloy a superlative absorbing capacity while the lowest energy absorbing capacity is observed for a 45° die angle. Its response to little displacement could have been responsible for this. More so, it can be observed that the heat-treated entry angles die formed mild steel enables slips and dislocation movement of the sample to take place with ease having a better elongation and

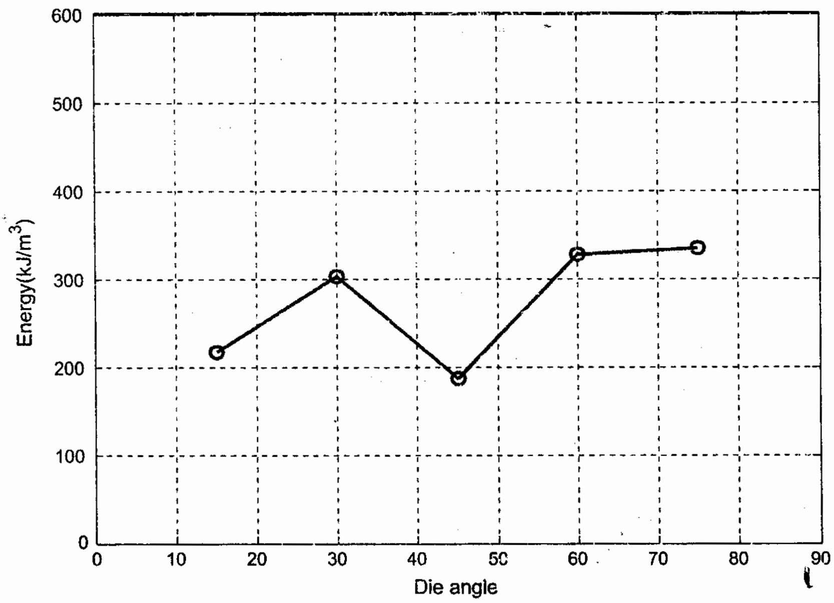

Fig. 5. Effect of energy absorbing capacity against die angle.

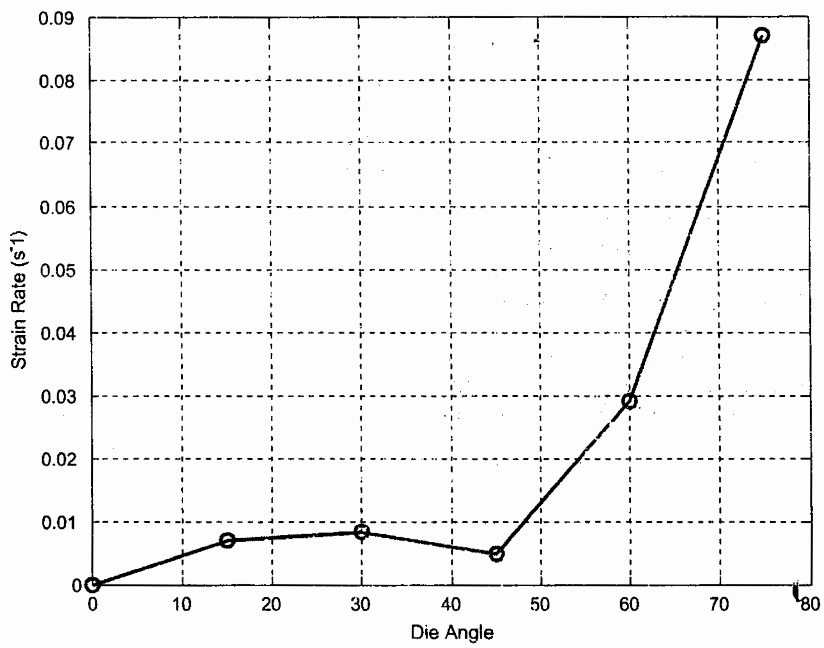

Fig. 6. Effect of strain rate against die angle.

deformation due to the precipitation and grain crystal orientation formed as a result of the cooling system and the high energy absorbed during quenching. Hence, the hardness of each extruded sample increases as the entry angle increases.

3.4. *Effect on strain rates*

The strain rate curve shown in Fig. 6 was calculated by using the equation [14]

$$\dot{\varepsilon} = \frac{6VD_C^3 \tan\alpha}{\left(D_C^3 - D_E^3\right)} 2\ln\frac{D_C}{D_E}$$

where V is the average ram speed, D_C is the container bore, D_E is the diameter of the extruded sample, and α is the die angle. According to [15] who affirmed that material having high strain rates possesses high compressive strengths and elongation with high pressure required achieving this, the strain rate curve in Fig. 6 justifies this statement. Product from each die whose strain rates followed an increasing order, correlates with its increasing maximum pressure except for the alloy extruded with a 45° die. Its low strain rate as compared with the rest could be a reason for its low energy absorbing tendency. The low displacement achieved should also be responsible for this despite having a maximum pressure of ≈850 MPa. This result has shown that the sample extruded with a 45° die exhibits the least ductility.

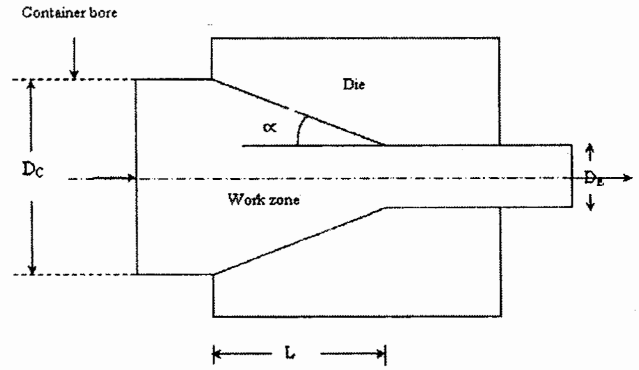

Fig. 7. Relationship among the deformation zone length, extrudate and initial billet diameters.

3.5. Deformation within the work zone

Within the work zone of the die whose geometry is shown in Fig. 7, the length of deformation zone L can be calculated mathematically [16] as

$$L = \frac{(D_C - D_E)}{2\tan\alpha}$$

where the initial diameter of the billet is same as the container bore diameter (25.1 mm). With the extrudate diameter and the die angle known, the length of the deformation zone was calculated. Fig. 8 shows that the length of the deformation zone reduces with increasing die angle and the reduction in length for each angle increase is approximately 50%. Result shows that with deformation length zone of ≅2 mm, axial elongation and lateral reduction of 15 mm and 10 mm respectively, can be achieved. The orderly reduction of die angles has culminated in the orderly reductions in the deformation zone length and orderly increase in axial billet elongations with an anomaly experienced with the 45° die. Each billet elongated more in the directions parallel to flow stresses than in directions perpendicular to them with the exception of a 45° die, which was the reverse case at the same constant temperature of deformation.

4. Conclusions

In this work, tool steel extrusion die geometry has been used to study the response of 6063 aluminum alloys to deformation and also, the effects of these responses on their toughness during engineering applications. From all indications, it is noted that:

- The highest magnitude of the maximum load is needed to give the alloy a maximum displacement on extruding with a 75° die. This makes it possess the best plastic deformation. A 60° die will be a second option as the billet deformed in a similar pattern but with a lesser displacement.
- Maximum loads needed to be applied on the alloy to respond to deformation increases with increasing die angle and this justifies why the maximum extrusion pressure for each angle follows the orderly trend.
- How far a punch will travel during deformation by extrusion does not depend on the magnitude of the maximum pressure alone but also, the geometry of the die coupled with the billet's inherent properties.
- The low flow stress (as compared with the rest) in a 15° die engendered the fastest and the best deformation case.
- The application of a product will be limited to certain loads since it has a low tendency to absorb energy unlike that of a 75° die whose energy absorbing property had the highest magnitude. The lowest value discovered with a 45° die could be attributed to its low displacement. For each die angle increase, axial elongation increased while the length of deformation zone decreased (with the exception of a 45° die whose elongation was the lowest). More so, each sample deformed more in the axial direction, except for the 45° die where reverse was the case.

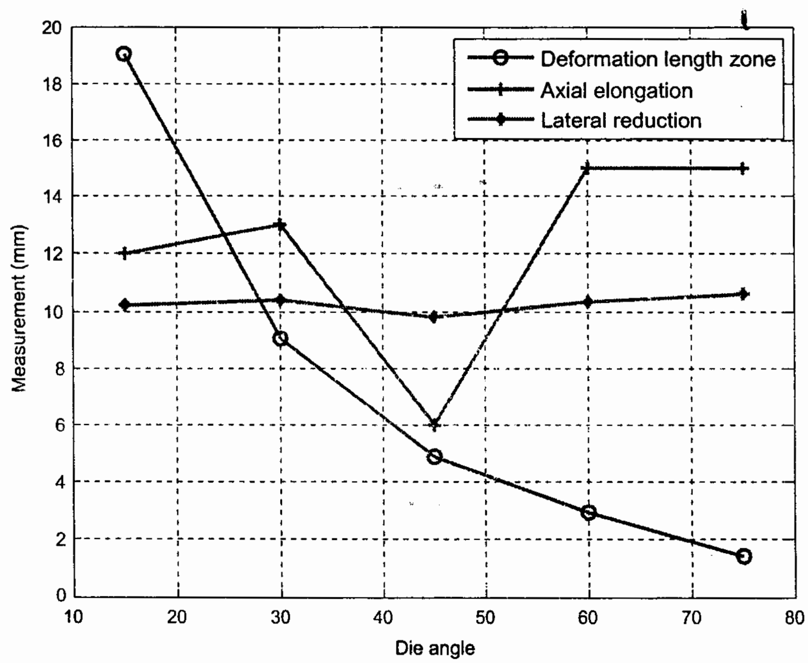

Fig. 8. Variations of deformation zone length, lateral reduction and axial elongation of samples with die angle.

From the overall view, using a 75° die will be the most preferable owing to the outstanding properties the alloy has over the rest of the dies.

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