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FEM study of extrusion complexity and dead metal zone

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ABSTRACT

Purpose: Quality of the extruded product and efficiency of the manufacturing process can be seriously affected by inconsistent metal flow through the extrusion die. Metal flow problems can also significantly reduce die life. Various researchers have investigated the effect of profile complexity on extrusion pressure, product quality, die life, etc. However, the relationship between shape complexity and metal flow through the extrusion die has not been studied in detail. Cold extrusion experiments on some solid profiles and simulations using the finite element method (FEM) have been used in this work to investigate the effect of profile complexity on dead metal zone and metal flow.

Design/methodology/approach: Cold extrusion experiments were performed using flat-face dies of different complexities. 3D finite element simulation was carried out using the commercial finite element packages ANSYS and ANSYS-LSDYNA.

Findings: Findings of this FEM study are that there appears to be no definite correlation between dead metal zone (DMZ) size and the currently existing definitions of extrusion shape complexity. Factors such as die profile symmetry and extrusion ratio may also play significant role in the formation of DMZ and distortion of metal flow through an extrusion die.

Practical implications: The study can be of direct utility in extrusion die design improvement, and reduction of extrusion defects related to metal flow.

Originality/value: The paper provides basis for a deeper understanding of the factors involved in the formation and development of dead metal zone (and related metal flow problems) in metal extrusion.

Keywords: Cold extrusion; Solid profiles; Shape complexity; Dead metal zone; Metal flow; Simulation (FEM)

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METHODOLOGY OF RESEARCH, ANALYSIS AND MODELLING

1. Introduction

In extrusion, the desired shape is obtained by plastic deformation of the billet material achieved by forcing it through a die. In any simple homogeneous and uniaxial compression (or tension), the metal flows plastically when the stress reaches the value of the flow stress. Once the applied force exceeds the shear strength of the material, sticking friction at the container surface becomes the dominant friction mode, and deformation takes place through shear in the bulk of the material.

Typical flow patterns observed in extrusion are shown in Fig.1 [1]. Flow pattern *S* is found in the absence of friction at the container and die interfaces, during extrusion of homogeneous materials. Flow pattern *A* is obtained in extrusion of homogeneous

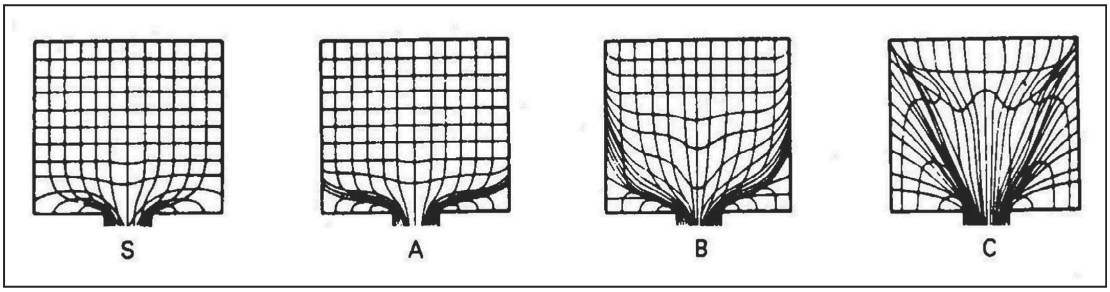


Fig. 1. Different types of metal flow in metal extrusion [1]

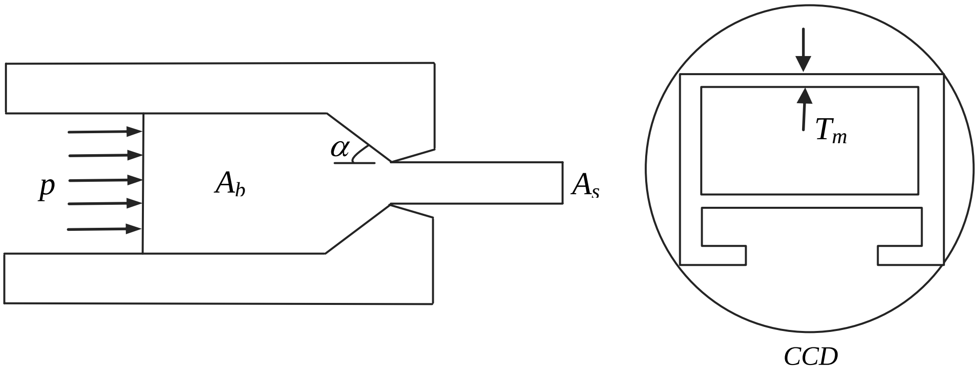


Fig. 2. Schematic illustration of the basic variables in direct extrusion

materials in the presence of friction at the die interface only. In the corner of the leading end of the billet, a separate metal zone (known as the *dead metal zone*) is formed between the die face and the container wall. Flow pattern *B* is obtained in homogeneous materials when there is friction at both die and container interfaces, resulting in an extended dead metal zone. Flow pattern *C* is observed with billets having inhomogeneous material properties or with nonuniform temperature distribution in the billet; a more extended dead metal zone is formed and the material undergoes a more severe shear deformation at the container wall. Studies show that for die cone semi-angles under 45º, the dead metal zone does not form [2-5].

Some of the basic parameters in direct (forward) extrusion are shown schematically in Fig-2. A_b is the initial billet area, p is the extrusion pressure, α is the die cone semi-angle, while A_s, T_m, and *CCD* are the final area, minimum wall thickness, and circumscribing circle diameter of the extruded section respectively. Extrusion ratio R is defined as the ratio of the billet area to the extruded section area ($R = A_b / A_s$). *Complexity* is a geometrical characteristic of an extrusion profile, relating to its *extrudability*. More complex profiles are intuitively associated with higher extrusion pressures, more inhomogeneous metal flow, and larger frequency and variety of product defects. Perhaps the most commonly quoted definition of complexity index [6] of an extrusion profile is

$$C_1 = P_s / A_s, \tag{1}$$

where P_s is the perimeter of the extruded section. A modified form of the above is

$$C_2 = P_s / W_s, \tag{2}$$

where W_s is section weight. Another complexity index, known as the *form factor* [7], is

$$C_3 = CCD / T_m. \tag{3}$$

The definition based on Altan's *shape factor* (function of perimeter ratio P_s/P_o), reported by Groover [8], is

$$C_4 = 0.98 + 0.02\left(\frac{P_s}{P_o}\right)^{2.25} \tag{4}$$

Here, P_o is the perimeter of a solid round shape of the same area as the extruded section. Based on a larger data set of actual industrial extrusions involving significant variation of profile complexities, the authors improved this definition to [9]:

$$C_5 = 0.95 + 0.05\left(\frac{P_s}{P_0}\right)^{1.5}. \tag{5}$$

Definition C_2 can be dropped from the analysis as it is essentially the same as definition C_1; $C_1 = P_s/A_s$ and $C_2 = P_s/W_s$ differ by only a constant multiple (material density).

It has been established by various studies that the size and shape of the dead metal zone, and the pattern and homogeneity of flow lines in extrusion are directly related to the die cone angle α, to friction at the billet-container interface, and to a lesser extent at the billet-die interface friction [10-13]. However, there are several other factors that can significantly affect extrusion metal flow. Unfortunately, these aspects have not been examined in detail in most of the published literature. Many studies use model materials (such as plasticine) and for metal flow study, lack of real material properties may contribute to inconsistencies with actual metal behavior. Numerical investigations are generally limited to the discussion of only one or two factors at a time. Also, enough experimental data is usually not available for satisfactory validation of numerical models, especially for metal flow pattern and dead metal zone analysis.

Though shape complexity is a very important parameter in extrusion, no published work can be found on the relationship (if any) between complexity and metal flow. In a previous work by the authors [14], effect of various process parameters (such as extrusion ratio, ram speed, extrusion pressure, and billet material) on metal flow and DMZ in metal extrusion have been looked into. The current paper reports some results from a detailed investigation of how the metal flow pattern and dead metal zone are affected by shape complexity in cold extrusion of solid profiles.

2. Experimentation

An extrusion chamber assembly (consisting of container, bolster and ram) and three different compatible dies were designed and manufactured in collaboration with the die manufacturing facility of a commercial extrusion setup. Geometric details of the three dies are shown through sketches in Fig-3. To emulate real world extrusion environment, these flat-face dies (90º die angle) were fabricated from H13 die steel using advanced machining techniques such as EDM, and were later subjected to standard heat treatment and surface hardening routines. Split billets of aluminum, lead, and Al-6063 were prepared to study metal flow patterns and dead metal zones. A 250-kN Instron universal testing machine, fitted with an extensometer (LVDT) and hooked up to a computer through a data logger, was used in the compression mode to perform and record the cold extrusion experiments.

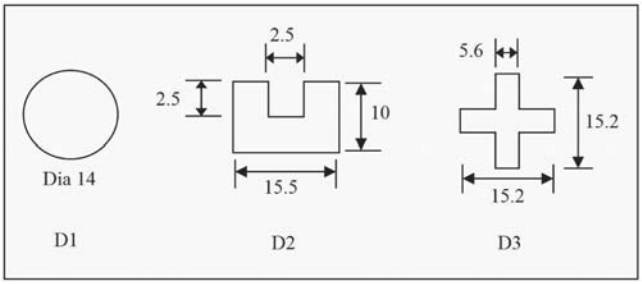


Fig. 3. Profiles and dimensions of the dies used in the study, diameter of the cylindrical billet being 19 mm for all cases

Each split billet was partially extruded, so that metal flow pattern and dead metal zone at the leading end of the unextruded billet could be studied. Various extrusion runs were carried out through each die, using the three billet materials in turn, and employing four different ram speeds (1 mm/min, 2 mm/min, 5 mm/min and 10 mm/min). All the experiments were carried out under cold conditions (room temperature). To avoid possible deterioration of the split surface due to excessive sticking friction, aluminum and Al-6063 billets were annealed to improve their ductility and flow characteristics, and a clear lubricant (petroleum jelly) was used during extrusion. Metal flow pattern and dead metal zone from each extruded sample were studied under a microscope, and recorded. Standard etching techniques were sometimes utilized for better visualization. Values of ram force exerted at different locations (as the ram advanced along the container) were recorded in the computer through the data logger.

3. Computer simulation

Extrusion runs on the three dies were simulated using the commercial finite element package ANSYS 7.0. To study the dynamic effects of changing ram speed, the software utilized was ANSYS-LSDYNA. Lead and aluminum being soft metals, further softened by annealing, billet material was modeled as elastic-perfectly plastic. As the container, die and billet surfaces were highly polished, and as a lubricant was also used, coefficient of friction was assumed to be negligible.

Due to the symmetrical nature of the solid circular die (die #1), a 2D model was deemed to be sufficient, with an axis of symmetry along the line representing the split billet surface; Fig-4. The 2D 6-node triangular structural solid element PLANE2 (possessing plasticity, large deformation and large strain capabilities) was used in the axisymmetric mode to model the material geometry in ANSYS. As ANSYS-LSDYNA has a different set of element types, the explicit 2D structural solid element PLANE162 (capable of representing translations, velocities and accelerations) was used for explicit dynamic analysis. Meshing was done using 1210 elements, grid refinement being used near the die entrance area of the billet to assist smooth flow of elements in the dead metal zone and surrounding regions. Contacts were defined at the billet-container and billet-die interfaces, container and die being modeled as rigid materials. Load was applied (in the form of displacement in ANSYS, and as velocity in ANSYS-LSDYNA) at the free end of the billet to replicate the ram pressure.

To represent the shape and geometry of the other two dies, 3D modeling had to be used. The 8-node 3D structural solid element SOLID164 was used for explicit dynamic analysis in ANSYS-LSDYNA. Die #2, having only one axis of symmetry, had to be modeled as shown in Fig-5. Model for die #3, possessing biaxial symmetry, is depicted in Fig-6. With grid refinement near the front end of the billet, 6737 elements were required by the solid model for die #2, and 21730 elements for die #3.

4. Results and discussion

Photographs of metal flow patterns and dead metal zones, viewed through a microscope, and graphical outputs from numerical simulation are appended below. Photographs are generally identified by a tag number: digits for the die # and ram speed are separated by a dash in each case. For instance, tag number 1-10 represents extrusion through die #1 at a ram speed of 10 mm/min.

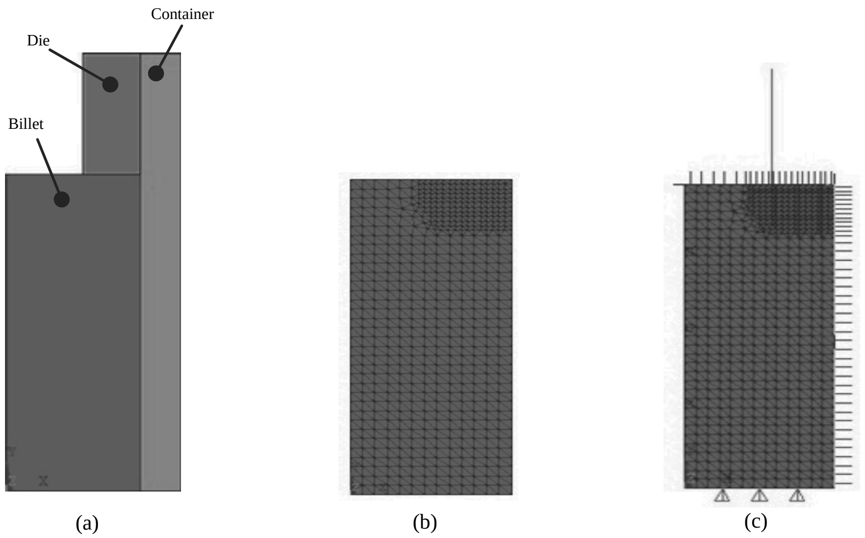


Fig. 4. 2D axisymmetric representation of the extrusion layout (a), finite element meshing of the billet (b), billet-container and billet-die contact pairs and applied load (c)

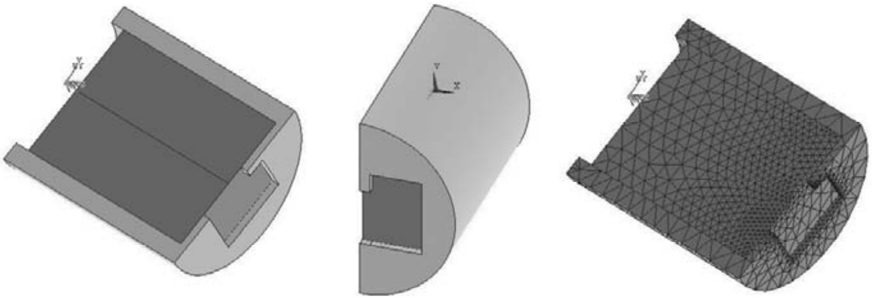


Fig. 5. Two views of the 3D geometry and finite element mesh for the billet and die model of die #2

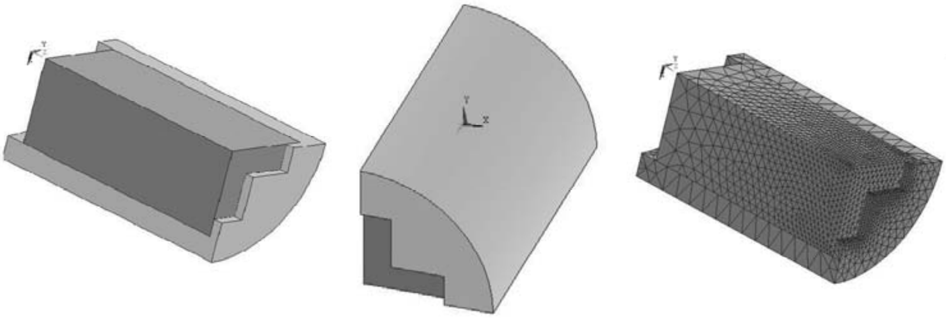


Fig. 6. Solid modeling and finite element meshing for the billet and die arrangement of die #3

Diagonal length of the dead metal zone area has been used in this work to represent the DMZ size. A larger DMZ is associated with increased internal friction, higher extrusion pressure, and more inhomogeneous metal flow. Increasing profile complexity also causes higher pressures and larger flow variations. It would then be intuitively expected that higher shape complexity should give rise to larger DMZ size.

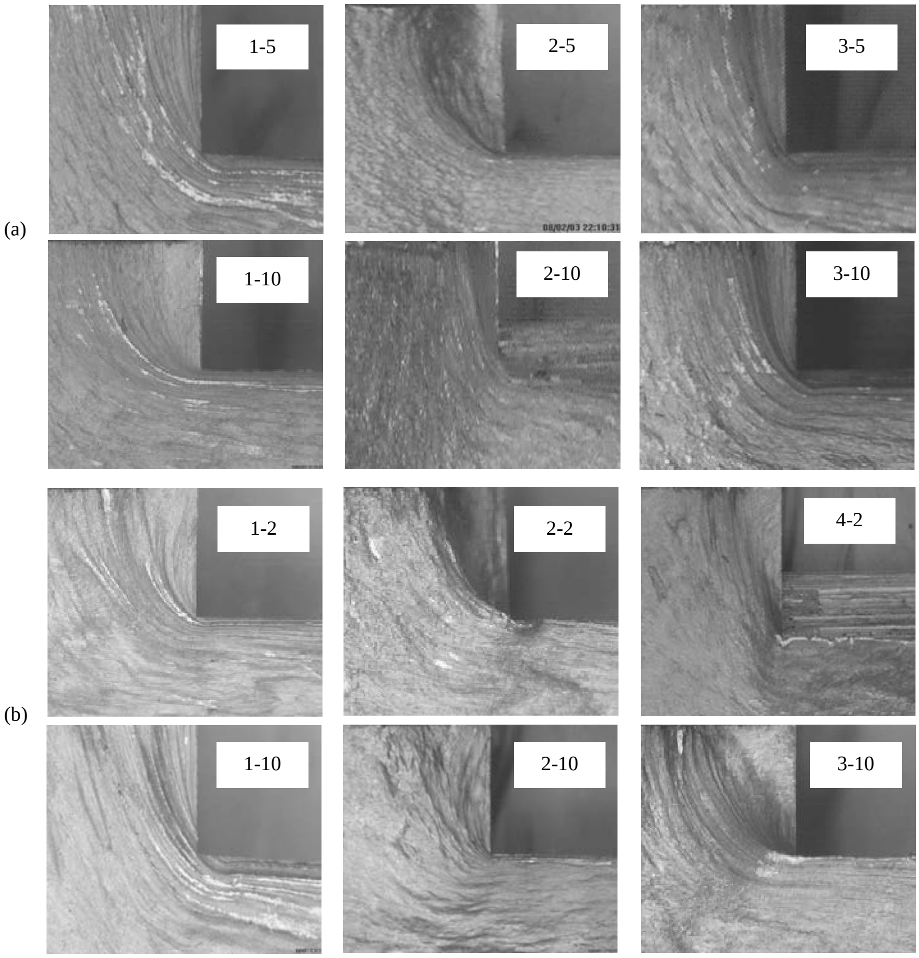


Fig. 7. Metal flow pattern and dead metal zone with changing shape complexity (profile # 1, 2, 3) at constant ram speeds of 2, 5, 10 mm/min: (a) Al-6063, (b) Aluminum

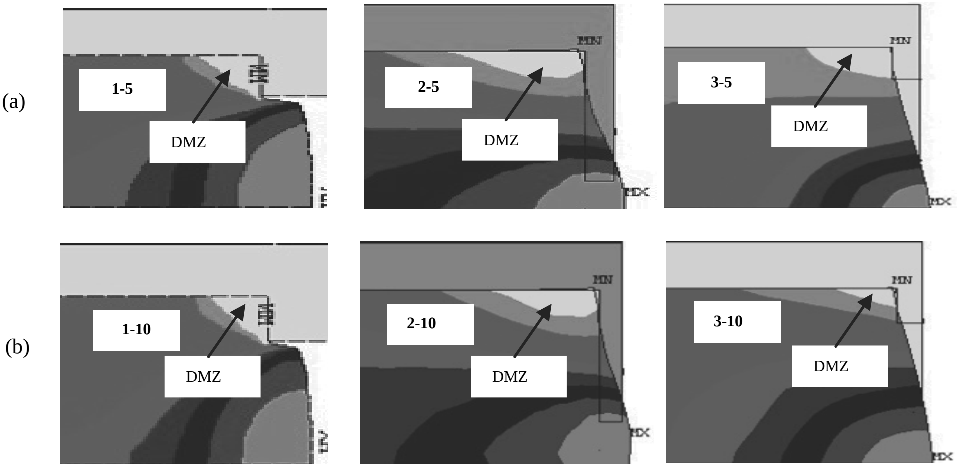


Fig. 8. DMZ size and metal flow in simulated extrusion of annealed aluminum through dies 1, 2, and 3 at ram speeds of 5 mm/min (a) and 10 mm/min (b)

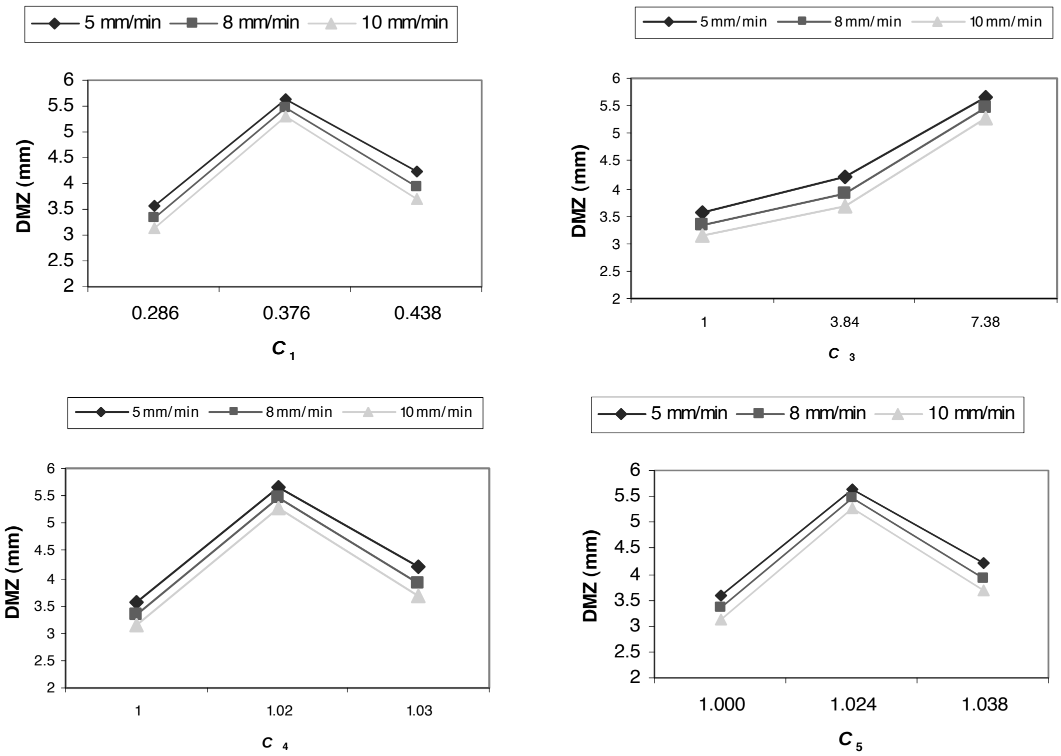
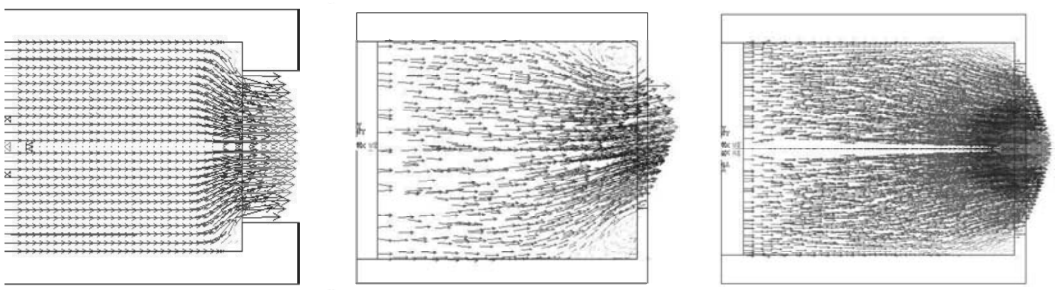


Fig. 9. Variation of DMZ size with increasing complexity for definitions C_1, C_3, C_4, and C_5; C_2 not included due to its similarity with C_1



(a) (b) (c)

Fig. 10. Simulated velocity profiles for the three dies: die #1 (a), die #2 (b), and die #3 (c)

Figure-7 shows magnified pictures of flow behavior with changing shape complexity of the die profile for two metals. For the alloy metal Al-6063, at the ram speed of 5 mm/min, *DMZ* size appears to be the largest die #2, somewhat smaller for die #1, and the smallest for die #3; DMZ size first increasing and then decreasing with increasing die complexity. At the higher extrusion speed of 10 mm/min, the *DMZ* first narrows down a little, and then broadens as complexity increases. Flow lines generally become steeper with increasing shape complexity, showing similar discrepancies as the *DMZ*. For pure aluminum, at both the speeds of 2 mm/min and 10 mm/min, the *DMZ* shows a trend of becoming larger and broader as the profile complexity increases. Flow lines generally become less steep and more rounded off.

Figure-8 shows outputs from simulated extrusion runs for the three dies at ram speeds of 5 mm/min and 10 mm/min in the case of pure aluminum. The same erratic behavior of DMZ size and metal flow pattern against changing die complexity can be observed as seen in actual experimental photographs above.

To get a clearer picture of this behavior, Fig-9 shows the variation of DMZ size against increasing profile complexity (for the three dies), according to different complexity definitions, at ram speeds of 5 mm/min, 8 mm/min, and 10 mm/min. Definition C_2 has been omitted due to its similarity with definition C_1. For definitions C_1, C_4, and C_5, DMZ size first increases and then decreases with increasing complexity. It should be noted that according to these three definitions, complexity increases from $D1$ to $D2$ to $D3$. For definition C_3 (which ranks $D2$ as the most complex), DMZ size increases with an increase in complexity.

These inconsistencies are rather perplexing. Had it been merely an experimental observation, the natural tendency would be to attribute these discrepancies to experimental errors or material inhomogeneities (which cannot be discounted altogether). However, numerical results amply corroborate the experimental findings. Other factors, not generally considered in complexity discussions, may be responsible for the irregular behavior. First of all, researchers agree that there are limitations to our understanding of the actual physics of material deformation in the extrusion process [15-16]. Secondly, though metal deformation is definitely affected by profile complexity, several contending issues are also involved:

(i) Symmetry of the die profile may play a significant role in metal flow. Though both $D2$ and $D3$ are somewhat more complicated than the simplest solid circular shape ($D1$), $D2$ has only a single axis of symmetry, while $D3$ possesses biaxial symmetry. Many prevalent definitions on the other hand attach a higher complexity rating to $D3$ because of its considerably larger perimeter. Effect of symmetry (or lack of it) on metal flow pattern needs to be investigated in more detail.

(ii) As pointed out above, extrusion ratio (R) has long been recognized as a very important profile parameter. As the listed complexity definitions do not include extrusion ratio as a defining parameter, it should be expected that a complexity-based rationalization of the metal flow pattern would not be satisfactory, based on these definitions.

(iii) Definition $C_3 = CCD/T_m$ is the only one that yields the consistent behavior of increasing DMZ size with increasing complexity. However, in an earlier work [17], this definition was found to be the weakest in terms of pressure prediction; so we cannot regard it as a robust indicator of complexity.

(iv) It was established in Qamar et al. [9] that complexity definition C_5 gives the best prediction for extrusion pressure in comparison with the four definitions found in published literature. However, even this definition proves to be inconsistent in explaining metal deformation behavior. This observation indicates that we need a still newer definition of extrusion shape complexity, incorporating all significant geometric parameters of a die profile (including extrusion ratio), and yielding better correspondence with experimental observations of DMZ size, pressure, etc.

A look at the velocity profiles obtained from extrusion simulations for the three dies (Fig-10) lends us further insight into the relationship between die complexity and metal flow. Pattern for the two biaxially symmetric dies (die #1 and die #3) is more homogeneous than that for the die with only one axis of symmetry. This would indicate that non-symmetric dies (quite common in commercial extrusion practice) would have even more inhomogeneous metal flow. Also, because of the asymmetrical geometry about the longitudinal axis, more metal flow is concentrated in the upper half of die #2 (Fig-10 (b)). This leads to higher pressures from one side of the exiting product, resulting in the extrusion defect known as *twists* or *bends*, requiring subsequent corrective action [18]. Such unbalanced metal flow may also lead to premature die failure. Die designers have to carefully look into these issues to guarantee optimum die life and minimum product defects.

5. Conclusions

Room temperature extrusion experiments have been performed on split billets of lead, aluminum, and Al-6063. Dies of three different solid profiles, made of H13 steel, are used. Extrusions have been carried out at four different ram speeds. Photographs of extruded billets studied under a microscope are used to investigate the regions and patterns of metal flow. Numerical simulations of the extrusion experiments are carried out to corroborate and extend the experimental observations. Five published definitions of extrusion shape complexity are used in the study.

With increasing complexity (according to each definition), distortion in metal flow and size of the dead metal zone do not increase, but show a decreasing-increasing pattern. This unexpected and erratic behavior may be partly due to variation in profile symmetry and extrusion ratio, and partly due to inconsistent and incomplete complexity definitions. This highlights the need for a better and more consistent definition of complexity index (including all important form features of a die profile). More experiments need to be conducted, together with more simulated runs (especially 3D), to further verify these observations and to provide information about situations and materials that cannot be easily experimented on.

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