SOME OBSERVATIONS ON PRESSURE DISTRIBUTION AND DIE FAILURE MODES IN HOT EXTRUSION

S.Z. Qamar[1], A.F.M. Arif[1], A. K. Sheikh[1], K.M. Al-Fuhaid[2]

1: Mechanical Engineering Department, KFUPM, Saudi Arabia
2: Aluminum Product Co. Ltd., Dammam, Saudi Arabia
E-mail: afmarif@kfupm.edu.sa

ABSTRACT

Extrusion is listed as a compressive deformation process in the classification of deformation practices given under DIN 8582 and 8583, and is usually carried out as a discontinuous process. In order to minimize defective products through proper die design and process control, a systematic analysis of extrusion process and tooling is thus required. To understand the process, and to determine optimum equipment and tooling requirements, the most important factor to be analyzed is perhaps the extrusion force or pressure.

Due to the high temperatures involved, and because of the complex thermo-mechanical changes occurring, commercial hot extrusion is a complicated process. Any analysis would thus depend upon some or all of a number of parameters such as billet material, die material and geometry, ram velocity, working conditions, and complexity of die shape.

This paper presents some results of ongoing studies about prediction of extrusion pressure and failure of dies in hot aluminum extrusion. The first part of the paper focuses on the inter-relationships of various basic parameters related to pressure variation. The second part describes some related product defects. In the last part, effect of die profile on modes of die failure is investigated.

Keywords: *Hot, extrusion, pressure, defects, failure modes, variation, ram speed, profile, tool, geometry, complexity index, shape factor, parameters*

الملخص

يعرف التشكيل بالبثق حسب المقننات العالمية لتصنيف عمليات التشوه (DIN 8582, 8583) على أنه عملية تشوه انضغاطي تحدث على نسق متقطع. وينبغي إجراء تحليل نمطي لعملية التشكيل بالبثق من أجل تقليل عيوب المشغولات عن طريق وضع تصميم سليم لقالب الصب ونظام للتحكم في عملية البثق، هذا وتعتبر قوة أو ضغط البثق من أهم العوامل التي يجب تحليلها من أجل فهم العملية ومن ثم القدرة على تحديد الأجهزة والأدوات المثلى المطلوبة لعملية البثق.

ونظراً لدرجات الحرارة المرتفعة المصاحبة لهذه العملية والتي تقترن بتغيرات ميكانيكية حرارية معقدة، فإن عملية البثق على الساخن تعتبر من العمليات المعقدة، ويعتمد تحليل هذه العملية على عدة عوامل مثل مادة الخام المعد للتشكيل ومادة قالب الصب وسرعة الكبس وظروف التشغيل ومدى تعقيد شكل قالب الصب.

وتقدم هذه الورقة بعض النتائج عن الدراسات الجارية من أجل التنبؤ بالضغط الملازم لعمليتي البثق وانهيار قالب الصب في عملية البثق على الساخن لخام الألومونيوم. ويركز الجزء الأول من الورقة على العلاقات الداخلية للعوامل الأساسية المختلفة المتعلقة بتغير الضغط، بينما يصف الجزء الثاني من الورقة بعض عيوب المنتج، كما يتم بحث تأثير شكل قالب الصب على أشكال انهياره في الجزء الأخير من الورقة.

1. INTRODUCTION

The process of extrusion converts a cast billet of solid metal into a continuous product of generally uniform cross-section by forcing it to flow through a die that is shaped to produce the required section profile. It is generally a hot working operation, the metal being heated to give it a suitable flow stress (degree of softness and ductility). In the modern process, cast billets of cylindrical shape, loaded into a composite cylinder (the container), are extruded through the die under pressure exerted by a ram, actuated hydraulically.

1.1 Extrusion Process

Figure-1 [Arif et al., 2001] illustrates the principle of the process, and the distinction between the two major working methods. In *direct extrusion*, the die is located at one end of the container and the metal to be extruded is pushed towards it, hence moving relative to the container. In the case of *indirect extrusion*, the die is placed on the end of the ram, which is bored out to allow passage of the extruded section, and moves through the container from one end, the opposite end being closed. It is generally more convenient for the container to travel and for the die (die assembly, nowadays) to be attached to a stationary ram.

Direct extrusion is the more widely utilized method, due to the difficulties in ram construction for the indirect process. The sequence of operations in commercial hot extrusion of aluminum is outlined in Fig-2 [Arif et al., 2001]. Round billets of Al-6063, of a diameter compatible with the size of the container in the extrusion press, are brought from the billet yard and stacked in front of the billet preheat ovens. Billets are then stage-wise heated to the desired temperature in a series of ovens. Next, they are sheared to the exact billet size required for each profile, and subsequently loaded into the extrusion chamber. Meanwhile, properly preheated die is loaded into the chamber, to be replaced by another one after the completion of one order. Once the ram pushes the entire billet through the die opening, a small remaining portion called the *discard* is sheared and sent to scrap. The extruded profile is gripped into the jaws of a puller, again discarding a small initial portion of the extrudate by saw cutting, and pulled over an air-cooled (through blowers) conveying system. This extruded length is stacked in the *stretching* area for straightening, and then cut to pieces of desired final length by a saw-cutting machine. The pieces may go to a *roll correction* station to remove any shape distortions, if required. Stacked batches then go through an *age hardening* in suitable furnaces

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process to improve the strength/hardness characteristics of the metal, before being sent to painting /anodizing shops, as per customer requirements.

The die and tooling arrangement employed in the direct extrusion of soft and medium grade aluminum alloys is shown in Fig-3 [Arif et al., 2001]. Functions of the various components shown are listed in Table-1.

1.2 Extrusion Parameters

Extrusion, especially at elevated temperatures, is a complex process involving thermo-mechanical changes in the shape, geometry and material of the workpiece. Any analysis would thus depend upon some or all of the following parameters: material properties of the workpiece and die, die geometry (die cone angle, reduction/extrusion ratio, die orifice location), mandrel size and layout, die/billet length, ram velocity, ram force, ambient conditions (working temperature, friction/lubrication at billet-container and billet-die interfaces, billet/die preheat temperatures), complexity of die shape, etc. Also, any analysis would depend upon the output requirements, such as stress distribution, strain distribution, strain-rate distribution, work done (especially plastic work), etc.

1.3 Shape Complexity

The complexity of an extrusion, according to a popular definition [Schey, 2000], is a function of the ratio of the perimeter to the cross-sectional area of the part, known as the *complexity index* or *shape factor*. Shapes are generally classified into three groups according to their complexity: solid, semi-hollow, and hollow.

The simplest definition of *complexity index* is

$$\zeta_1 = \textit{Perimeter / Cross-sectional Area}.$$

A modified form of the above is

$$\zeta_2 = \textit{Perimeter / Weight}.$$

In order to normalize the quantity, we can use weight per unit length instead of weight.

The following form of *shape factor* has been proposed for extrusion process [Mielnik, 1991]:

$$\zeta_3 = f\,(L_e / L_o),$$

where L_e and L_o are the perimeter of the extruded shape under consideration, and the perimeter of a round shape of the same cross-sectional area, respectively.

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Another complexity factor known as *form factor* [Laue and Stenger, 1981] is given by

$$\zeta_4 = CCD / t_{min.},$$

where CCD is the circumscribing circle diameter and t_{min} is the minimum wall thickness.

The first two definitions have been used in this paper for their relative simplicity and ease of calculation.

1.4 Current Work

This paper summarizes some of the findings from two ongoing studies about (i) prediction of extrusion pressure, and (ii) failure of dies in hot aluminum extrusion. The first investigation focuses on the inter-relationships among three basic parameters: *ram pressure* (force with which the ram/plunger pushes the billet through the die profile, divided by the billet or container area), *strain rate* (rate of relative deformation that the billet undergoes in transforming to the extruded shape, the value being directly dependent on the *ram speed*), and *tool complexity* (shape complexity of the die profile, measured by a factor called *complexity index*). The second work explores the effect of die profile (complexity) on modes of die failure from three different perspectives: (a) overall and class-wise break-up of failure modes, (b) failure analysis for dies of different complexities, and (c) shape-wise breakdown of each failure mode.

For the pressure-variation study, various experiments in direct (forward) hot extrusion were conducted in collaboration with a local industrial setup, Aluminum Products Company (ALUPCO), Dammam, Saudi Arabia. All experiments were run on a fully computerized 3500-ton capacity SMS-Hasenclever press, on-line real-time data being directly available through the CADEX (Computer-Aided Direct Extrusion) software package. For the tool-failure mechanism investigation, a total of 616 die failures involving 17 different die profiles were studied. The same die material (H-13 steel) and the same billet material (Al-6063) were used in all experiments, under almost similar conditions (temperature range of about 425-475 ºC, without the use of any lubricants).

2. EXTRUSION PRESSURE VARIATION

Figure-4 shows the solid, hollow, and semi-hollow profiles on which the pressure-variation experiments were conducted, while Table-2 lists indices giving their shape complexity (based on two popular definitions of the complexity index ζ). Profile names start with a letter indicating profile type (*S* for solid, and *H* for hollow) followed by a number indicating its complexity index rating in an ascending order ('1' for lowest ζ, '2' for next higher ζ, and so on). The profiles are arranged in an increasing shape complexity order. There are often multiple cavities in the same die to give a higher production rate, depending on the size of the extruded profiles and the die size. The table therefore also lists the number of cavities against

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each profile, to give a better understanding of the process. Another very important process parameter, the *extrusion ratio* ***R*** (ratio of billet/container area to the extruded area) is also given for each die. Some significant observations, as evidenced from Fig-5, are as follows:

2.1 Pressure Variation Against Ram Position

In all the experiments conducted, variation of ram pressure was recorded at fixed intervals as the ram advances along the container. Apart from the sharp peak (sudden increase and then decrease) in the start-up area, pressure gradually drops down as the plunger moves forward along the container, validating expected pressure behavior. Also, most of the plots exhibit relatively smooth and regular pressure variation, while some curves show partial fluctuation. This could be attributed to automatic machine adjustments and experimental aberrations such as physical interruptions in the process (billet loading mechanism not working properly, interruptions due to preheating ovens malfunctioning, etc).

2.2 Pressure v/s Shape Complexity at Constant Ram speed

When the ram speed is kept constant, pressure curves for more complex profiles are generally higher than those of less complex ones. In a couple of cases, solid dies having similar or slightly higher ζ-values than hollow ones, have lower pressure curves. Similarly, one higher-ζ hollow profile has lesser pressure values than two other hollow shapes. Apart from experimental anomalies, this highlights the need for a better definition of die complexity.

2.3 Pressure v/s Ram speed for Fixed Shape Complexity

When the die profile is the same, there is a general trend of higher-pressure curves for higher ram speeds. Outlier behaviour suggests that (i) pressure distribution is usually more regular and uniform for profiles with biaxial symmetry, and that (ii) a definition of shape complexity based only on perimeter and area/weight does not appear to be sufficient.

2.4 Shape Complexity

Two definitions have been used here to calculate the complexity index ζ, both yielding the same ordering in terms of shape complexity. Almost all observations tend to suggest that pressure variation in extrusion is inherently linked with shape complexity. Thus the premise, that a pressure-prediction module (based on a reference pressure-curve of a simple die profile) can be developed in terms of complexity indexes, appears to be a valid one. Some of the observations are rather difficult to explain on scientific grounds, indicating that (i) more experiments need to be conducted, using a larger spread of die complexity and under better data reliability conditions, and (ii) more definitions of ζ need to be investigated, or an entirely new definition formulated, to a give a better and more consistent shape complexity ordering.

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3. EXTRUSION DEFECTS

Defects in extrusion may arise due to a variety of reasons. The ones more pertinent to this study are listed below.

3.1 Defects Related to Temperature and Speed

Some defects are directly related to the temperature rise generated at the surface of the product as it is deformed. Temperature rises rapidly with exit speed, as there is a greater rate of work input and reduced heat loss to tooling. At a certain exit speed, local melting might occur. This condition gives rise to the defect referred to as *hot shortness* or *U-shaped cracking*.

Surface cracking occurs by local tensile failure at areas of melting due to the tensile stress state present at the edge of the die bearing. If the exit temperature or speed is too high, *tearing* initially starts at the edges of the extrusion and then develops over the remainder of the surface, giving rise to the defect commonly called *fir-tree cracking* or *speed cracking* (circumferential surface cracks); Fig-6(a).

3.2 Die Profile Related Defects

Extrusion defects that originate in die imperfections, especially those associated with shape complexity, are quite common. *Black lines* are burnt surfaces on the extrudate due to a local high pressure in the extrusion press; Fig-6(b). This can happen in the welding chamber for hollow dies, or at any aberration in a solid die that results in a localized high pressure. The defect generally becomes visible after etching.

Several factors can cause dissimilar metal flow in the cavities of a multi-hole die: die openings (cavities) not being perfectly aligned (centered) with respect to the container; different wall thicknesses in the section design, etc. Material flow is thus faster on one side, resulting in *twists* and *bends*; Fig-6(c).

If the die surface is not smooth enough (due to wear, lack of hardness, hard inclusions on die surface), *scratches* might appear on the extruded surface; Fig-6(d).

In multicavity dies, extruded sections may rub against each other while coming out of the die openings. This chafing of hot extruded sections creates *hot rub marks*. They usually become visible after etching/anodizing.

Based on various industry standards prescribing dimensional tolerances, an extruded section may be rejected due to *dimensional defects*. A section can be *out of angle* due to nonuniform metal flow in the die, or because of the problems on the die-bearing surface. A *concave* or

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convex or *uneven surface* is another such problem based on differential rates of metal flow in the die. A section is termed *off dimensions* if it is out of shape, or it has *uneven wall thickness*. It can happen, for instance, if the mandrel in hollow extrusion is not properly centered.

4. DIE FAILURE

The bulk of aluminum extrusion finds application in the construction industry. This has led to a universal jargon, originating in the construction sector, describing extrusion press and tooling, profile features, and die-failure related issues.

4.1 Profile Terminology

Some of the more common features shared by most of the extrusion profiles are shown in Fig-7. A partially open rectangular extension, usually attached to a hollow profile, is called a *tongue*. The slotted groove on which a rubber lining is later fitted, typically for door and window brackets, is known as a *path* or *brush path*. Any sharp corner or sudden cross-section change is referred to as a *corner*. The flow distribution/control passages provided in the feeder plate (solid die) or mandrel (hollow die) are called *cavities*. Small appendages to the main profile, in effect minor sub-profiles, are termed *details*. A *screw hole/boss*, as the name implies, is used later for fastening the extruded section to a structure. A very small protrusion, either sharp or rounded, is designated as a *tip*.

4.2 Die Failure Mechanisms

A *crack* refers to a visible, generally uneven fissure on the surface as opposed to a *break* that results in the component being actually broken into two or more pieces. A *chip-off* indicates a small piece chipping off from a surface, not a large enough chunk to categories it as a break. *Washout* of a surface implies tiny but significant individual or aggregate craters and depressions caused by erosion/pitting. Plastic deformation due to thermal and/or mechanical stresses may result in a component or part of it being *deflected* or *bent*. Severe wear and tear caused by factors such as impact, hard metal impurities in the billet, or any other mechanism not classified above, is termed as *damage*.

The more prevalent terms used by the industry to identify failure mechanisms related to various die/tooling features commonly encountered in construction aluminum extrusion are listed in Table-3. For purposes of analysis, they have been divided into five major classes. All fatigue related failures, surface fatigue, and microchipping/cracking due to mechanical and/or thermal stresses are categorized as *fracture*. Gradual surface deterioration due to various factors is classified as *wear*. Going out of shape (bending or deflection) of a part or sub-component owing to excessive plastic deformation is labeled as *deflection*. When failure is due to a combination of any of the above-mentioned factors, it is termed *mixed-mode*. Failures that cannot be precisely categorized into one of the above, such as overall softening of the die or bearing area due to a fault in the nitriding oven, fall under the *miscellaneous* category. When the die set has to be scrapped due to any failure occurring in the mandrel (only for hollow and semi-hollow dies), the classification is *mandrel failure*.

4.3 Die Failure Modes and Profile Complexity

Table-4 lists all the failure mechanisms, categorized into the five failure modes discussed above. *Die type* tells us whether the die is of the solid (S), hollow (H) or semi-hollow (SH) profile. *Number of cavities* refers to the number of profile cavities arranged in a prescribed layout in a multiple-cavity die. Normalized failure probabilities have been worked out for each failure mechanism, and for each major failure mode.

Figure-8(a) shows an overall breakup of die failure modes. It is quite evident that the dominant failure mode, for all die shapes taken on the whole, is fatigue fracture (46%) followed by wear (26%) and then deflection (19%). Mixed failure modes (4%) and the various failure mechanisms categorized as miscellaneous (2%) comprise the remaining die failure patterns. Failures caused at the mandrel (including all the three modes: fracture, wear and deflection) constitute 3% of the total failures. The observations support intuitive reasoning. With the large number of sharp corners, projections and protrusions, slots and grooves, combination of thin and thick sections, and the general lack of symmetry present in most of the solid as well as hollow profiles, fatigue-based failures (both thermal and deformation and deflection of critical sections should closely follow the other two failure modes. The rest of the failure classes are obviously not major players in the die failure arena.

It is interesting to note from Fig-8(b) that the leading fracture-type failure is that related to path/brush-path breakdown. Again, in retrospect, it is quite obvious that in the aluminum construction industry, brush paths are the most frequently repeated critical section and thus play a predominant role in fatigue failures.

Figure-8(c) indicates that wear failures are almost exclusively of the dimension-change type (oversize and overweight are also categories of the same). In this case, even though only part of the bearing surface has been worn out, the extrusions are so much out-of-dimensions that they fail to pass dimensional inspection. Thus most of the dies have to be scrapped much before complete washout of the die land. It should be pointed out here that this die rejection takes place after several corrections, cleaning and renitriding cycles have already taken place, and repair of the bearing surface is no more feasible.

Again, as should be expected, deflection-type failures [Fig-8(d)] are almost exclusively found at the bearing. With uneven and unsymmetrical sections, and maximum pressures and friction forces working here, the bearing is the most likely location to be excessively plastically deformed. As tongues are minor bearing surfaces in themselves, they are the next obvious deflection concentration locations; but as tongues are not present in most of the dies, their

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contribution is only a small fraction of the total deflection failures.mechanical) should be expected to be the principal failure mode. With the continually repeated friction between the extremely hard aluminum-oxide layer on the billet and the iron-oxide layer at the bearing surface, and the repeated renitriding during die maintenance cycles, wear at the die land should be the likely second major failure mode. Also, with the elevated temperatures and pressures involved, and the necessity of relatively high extrusion speeds aimed at higher productivity, plastic

5. CONCLUSIONS

Experiments were conducted to investigate the effect of ram speed and tool complexity on the variation of extrusion pressure. At constant ram speeds, pressure curves for more complex profiles were generally higher than those of less complex ones. Deviations from this behavior emphasize the need for an improved definition of die shape complexity. For fixed shape complexity, pressure curves are generally higher for higher speeds. Departure from this trend hints at more uniform pressure variation for profiles with biaxial symmetry, and again underlines the importance of a better die complexity definition.

Product defects originating in profile geometry and extrusion temperature and speed were studied. Defects such as hot shortness, tearing, and fir-tree cracking originate due to higher temperatures and speeds. Black lines, twists ands bends, scratches, hot rub marks, uneven surface, uneven wall thickness, etc are defects related to the die profile.

Failure data were collected for a variety of aluminum extrusion dies used extensively in the construction sector. Terminology related to failure mechanisms, prevalent in the industry, was introduced such as crack, break, chip-off, washout, deflected/bent, damage, etc. Major die failure modes identified were fracture, wear, deflection, mixed-mode, and mandrel-related. On an overall basis, fatigue fracture was found to be the dominant failure contributor. In fracture-type failures, breakdown of brush-path was the leading factor. Majority of wear-type failures were of the dimension-change category. Failures of the deflection class were mostly found to occur in the die bearing area.

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Table-1 Aluminum extrusion press and tooling

Component	Function
Die	Produces the extrusion shape/profile
Die Holder / Ring	Holds the die, the feeder plate and the die backer together
Die Backer	Provides support to the die against collapse or fracture
Bolster	Transfers the extrusion load from the die to the pressure ring/pad
Pressure Ring/Pad	Transfers the extrusion load from the bolster to the press platen and also guards against bolster deflection
Die Carrier/Slide	Holds together the complete die set (bolster and die ring)
Feeder Plate	Placed in front of the die, it balances the metal flow and allows continuous extrusion without breaks
Liner	Provides protection against thermal and mechanical stresses to the large and expensive container
Stem	It is fitted with the main ram to force the billet trough the container
Dummy Pad	Floating or fitted in front of the stem, it protects the life of the costly stem

Table-2 Some geometrical details of tool profiles used in the experiments

Profile Number	Profile Type	Number of Cavities	Extrusion Ratio (R)	Complexity Index (ζ_1)	Complexity Index (ζ_2)
S1	Solid	2	36	0.143	0.053
H2	Hollow	1	71	0.366	0.135
S3	Solid	3	60	0.513	0.19
S4	Solid	3	67	0.559	0.207
H5	Hollow	4	79	0.94	0.346
S6	Solid	2	59	0.946	0.35
H7	Hollow	4	80	1.023	0.379
H8	Hollow	4	82	1.097	0.407
H9	Hollow	4	96	1.13	0.421
H10	Hollow	4	80	1.739	0.645

Table-3 Categorization of Die Failure Mechanisms

Failure Mode	Failure Mechanisms
Fracture (F)	Path/brush-path broken (PB/BPB), Bearing chip-off (BCO), Corner crack (CC), Die broken/cracked (DB/DC), Bearing broken/cracked (BB/BC), Cavity broken (CvB), Detail broken (DtB), Screw/screw-hole broken (ScB/SHB), Surface cracked (SfC), Tongue broken/cracked (TB/TC), Tip broken (TpB)
Wear (W)	Bearing wash-out (BWO), Dimension change/ oversize/overweight (DimC/OS/OW)
Deflection (D)	Cavity/die deflected (CvD/Df), Tongue bent/deflected (TBt/TDf)
Mixed mode (Mx)	
Miscellaneous (Msc)	Bearing/cavity damage (BDm/CvDm), Die/bearing soft (DS/BS), nitriding oven failure (NOF)
Mandrel failure (M)	Mandrel broken/cracked/ deflected (MB/MC/MDf)

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Table-4 Failures of dies of different types by various failure modes

DIE DETAILS			**FAILURES**						
Die #	**Die Type**	**No. of Cavities**	**Fracture**	**Wear**	**Deflection**	**Mixed-Mode**	**Miscellaneous**	**Mandrel**	**Die-Type Total**
H9025	H	3		3	1				**4**
		4	2	21	16	3	1	2	**45**
H9036	H	2	13	7	1	1		3	**25**
		3	21	2	1		1	1	**26**
H9054	H	1		8	2	2		5	**17**
		2	1	3	1				**5**
H9056	H	2	2	16	15	3		2	**38**
H9077	H	1		1		1			**2**
		2	1	7	9	2			**19**
H9079	H	2			1				**1**
		3		4	5				**9**
		4		2	1	1			**4**
H9330	H	4	1	8	12	2			**23**
H9383	H	1		6	14	2		1	**23**
S9021	S	2	10	5	1	2			**18**
S9007	S	1	47	2		1	1		**51**
		2	13						**13**
S9018	S	1	25	7	5	3			**40**
		2	17	2	1		2		**22**
S9035	S	2	20	1					**21**
		4	43	5					**48**
S9067	S	1	14	2			2		**18**
S9068	S	1	6	5					**11**
S9087	S	1	16	11			2		**29**
H9033	SH	2		5	3	2			**10**
		3	4	8	17		2		**31**
H9034	SH	2	20	15	5		1	3	**44**
		3	12	2	5				**19**
	Failure-Mode Total		**288**	**158**	**116**	**25**	**12**	**17**	**616**

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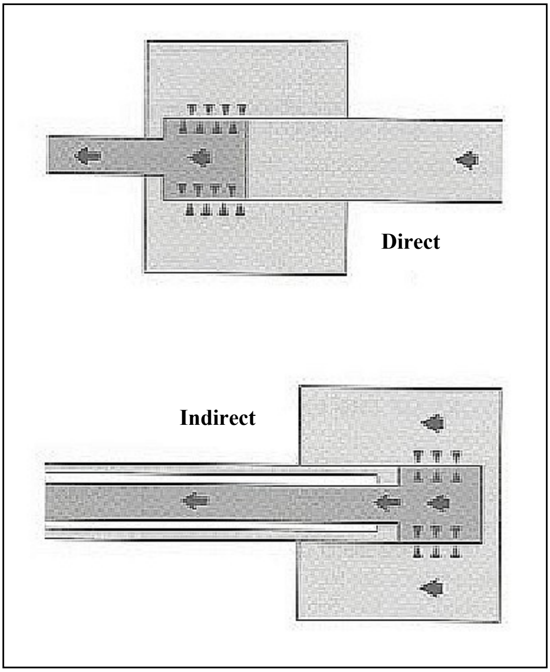

Figure-1 Schematic diagram showing direct and indirect Extrusion [Sheppard, 1999].

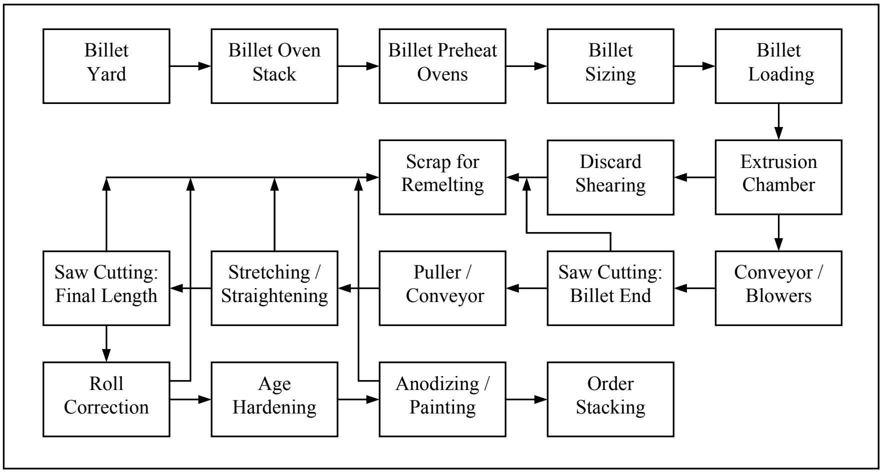

Figure-2 Process flow in hot extrusion of Al-6063 [Arif et al., 2001]

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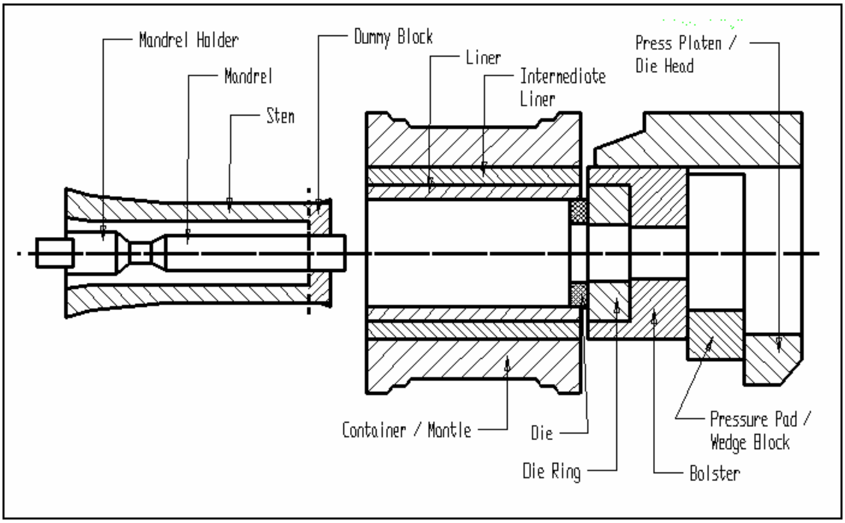

Figure-3 Die and tooling configuration for hot extrusion of Al-6063 [Arif et al., 2001]

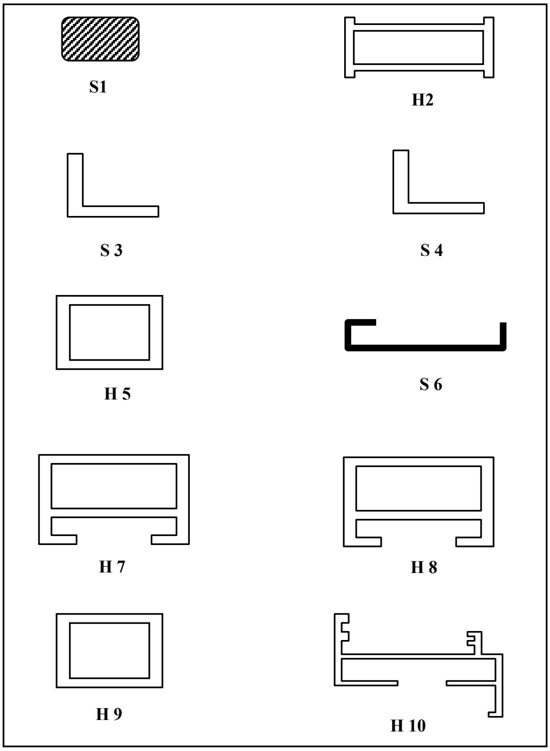

Figure-4. Die profiles used in the pressure-variation study.

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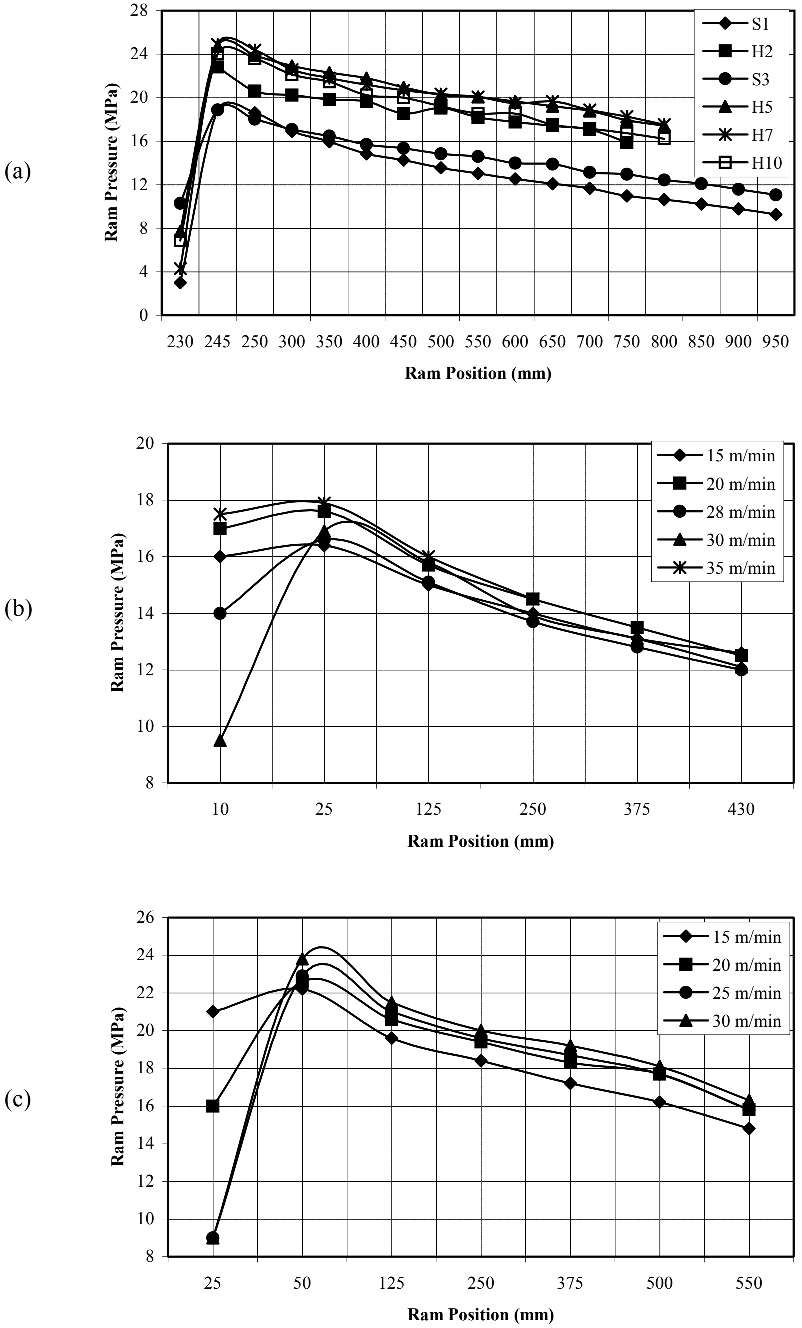
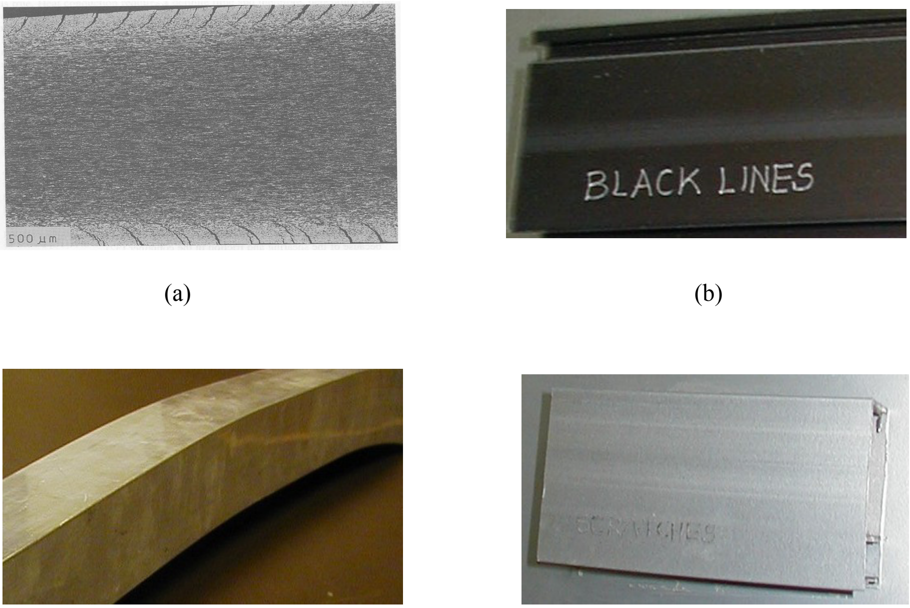


Figure-5 (a) Ram force vs ram position for different ζ at constant ram speed;
(b) Ram pressure vs ram position of a solid profile at different ram speeds;
(c) Ram pressure vs ram position of a hollow profile at different ram speeds



(a) (b)

(c) (d)

Figure-6 Product defects related to temperature, ram speed, and die complexity: surface cracking (a), black lines (b), twist/bend (c), scratches (d).

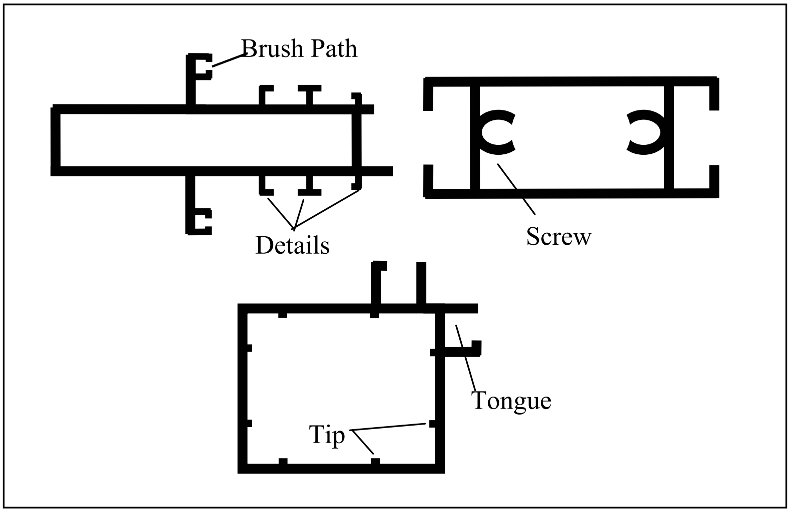


Figure-7 Some profile features commonly found in construction aluminum sections.

Top

(a) (b)

(c) (d)

Figure-8 (a) Overall breakup of die failure modes; (b) Breakup of fracture-type failures; (c) Breakup of wear-type failures; (d) Breakup of deflection-type failures