PRODUCT DEFECTS IN ALUMINUM EXTRUSION AND THEIR IMPACT ON OPERATIONAL COST

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ABSTRACT

Commercial hot extrusion of aluminum involves different operations, such as billet preheating and shearing, loading and deformation, stretching and roll correction, age hardening, and painting/anodizing. Because of the high tool and equipment investment involved, it is vital to understand the relationship between the condition of the extrusion press and ancillary equipment and their performance measured in terms of productivity and recovery. This in turn necessitates an understanding of the contributing and controlling factors related to product defects in extrusion.

The quality of any extruded product is a function of various factors, such as chemical composition, geometrical dimensions, appearance and regularity of the microstructure, variation of mechanical properties over the extruded length and cross section, and surface finish. Extrusion defects may arise in extruded products from the starting material or billet, the deformation process itself, or from other post-processing corrective measures. An attempt is made in the first part of the paper to describe various types of product defects in commercial aluminum extrusion, to trace their mechanical and metallurgical causes, and to suggest viable corrective/preventive measures. Some defects not covered in earlier works have been described, exhibits of actual defects from the industry are presented that are not available in published literature, a complete category-wise defect classification has been carried out that has not been attempted in any previous study, some preventive/remedial measures prevalent in the industry are elucidated that cannot be found in earlier studies.

As all unacceptable defects involve rework or rejection, they directly lead to production losses. The latter part of the paper proposes a generalized cost model for hot metalworking (specifically, extrusion), based on the probability of producing a defective part at each processing or post-processing stage. Real world data from local industry is used for partial cost analysis.

Keywords: *Hot metal forming, extrusion, anodizing, painting, defects, origin, classification, flow patterns, cost, model, analysis*

الملخص

تشمل عملية بثق الألومنيوم التجارية عدة عمليات تشغيل مثل التسخين المسبق للخام المعد للتشكيل ، عملية القص، والتحميل والتشوه والإستطالة وعملية تصحيح الدلفنة والتعتيق والطلاء، ويعتبر فهم العلاقة بين حالة مكبس البثـق والأجهزة الملحقة وكفائتها من ناحية الإنتاجية حيوياً لهذه العملية التي يلازمها استثماراً مرتفعاً في نفقات الأدوات والأجهزة، كما يستلزم ذلك أيضاً فهماً جيداً للعوامل المساهمة والمتحكمة في عيوب المنتج من عملية البثق.

وتعتبر جودة المنتج من عملية البثق نتيجة لعدة عوامل مثل التركيب الكيميائي، والقياسات الهندسية ومظهر البنـاء الداخلي للخام وتغير الصفات الميكانيكية على الطول المبثوق ومساحة المقطع وأملسية السطح. ويمكـن أن تنـتج عيوب المشغولات بداية من الخام المعد للتشغيل أو من عملية التشكيل أو من بعض عمليات التصحيح التـي تلـي عملية البثق. ويركز الجزء الأول من هذه الورقة على وصف العيوب المختلفة الناتجة في عمليةبثق الألومونيـوم تجارياً ومحاولة تتبع أسبابها الميكانيكية أو الناتجة عن تكوين المعدن، مع وضع اقتراحات لمنع أو تصحيح هـذه العيوب، حيث أنه من المعروف أن العيوب الغير مقبولة تستلزم إعادة تشغيل أو رفض المنتج مما يترتـب عليـه زيادة في تكاليف التشغيل. ويمثل الجزء الثاني من هذه الورقة نموذج تكلفة مقترح لتشغيل المعادن على السـاخن وخاصة عملية البثق، ويعتمد هذا النموذج على احتمالات إنتاج جزء معيب من كل عملية تشغيل أو عملية مابعـد التشغيل. هذا ويتم استخدام بيانات حقيقية من الصناعات المحلية لعمل تحليل حسابات التكلفة.

1. INTRODUCTION

Commercial aluminum extrusion is generally a hot metal-forming operation. The basic process consists of forcing a preheated billet (usually round), placed in a heated chamber, through a die opening by a ram. A typical process flow is outlined in Fig-1 [Arif et al., 2001]; there might be slight deviations from this general arrangement from plant to plant.

1.1 Defects in Extrusion

An extruded profile may be deemed to be a reject (unacceptable product that does not fulfill standard or customer specifications), owing to any of the following reasons:

(i) Defective billets (slag/impurity inclusion, scales/flakes, internal cracks, undissolved oxides, etc)

(ii) Faulty or unsuitable tooling (billet and die preheat furnaces, dies/mandrels, dimensional correction equipment, etc)

(iii) Defects arising during extrusion (inappropriate extrusion pressure, chamber temperature, friction, ram speed, etc)

(iv) Flaws resulting in the course of post-extrusion operations (saw cutting, stretching/straightening, roll correction, age hardening, anodizing, painting, etc).

1.2 Current Work

Some researchers have attempted to analyze a few of the process defects encountered in extrusion. However, no exhaustive and systematic study has yet been reported in this area. That is why many defects do not have a unique name, different workers coining different terms for the same flaw from time to time. Also, very few references are available on properly categorizing extrusion related flaws. Moreover, only a handful of researchers have come up with appropriate preventive or corrective measures for these defects. Some of the salient features that differentiate the current work from hitherto published material are:

(i) Exhaustive definition, together with visual exhibits in most of the cases, of all defects arising in aluminum extrusion

(ii) Scientific and systematic classification of extrusion related defects into logical categories

(iii) Probe into the causes (mechanical, metallurgical, equipment or process related) of all the defects, and description of practical remedies and precautionary measures generally carried out in the industry.

Wherever not referenced, visual exhibits are photographs of actual defect samples collected over time from the industry. Pictures of some of the defects could not be included due to space restrictions.

Any attempt at analyzing the productivity and profitability of a production process would be incomplete without a suitable cost analysis. Unfortunately, related literature does not provide any such reference specifically targeted at the extrusion industry. The current paper proposes a cost model to determine the cost of rejects during any given period of study that incorporates the probability of producing a defective section at each stage in a typical extrusion setup. The model is then used to partially study rejection patterns over the last few years, based on data from a local industry.

2. METAL-FLOW RELATED DEFECTS

These extrusion defects are the result of nonuniformity and nonhomogeneity of metal flow in the container. The four characteristic patterns in direct extrusion using a square die are shown in Fig-2 [Laue and Stenger, 1981], classified according to the increasing order of nonuniformity of flow. Pattern ***S*** is characterized by the maximum possible uniformity of flow in the container. Flow type ***A*** occurs when there is virtually no friction between the container and the billet, but significant friction at the surface of the die and its holder. Flow pattern ***B*** occurs if there is friction at both the container wall and at the surfaces of the die and die holder. Also, the dead metal zone is not completely rigid and can influence (to a limited degree) the flow of the metal. Type ***C*** flow occurs when the friction is high (as in type *B*) and the flow stress of the material in the cooler peripheral regions of the billet is considerably higher than that in the center.

Funnel formation is the metal-flow related defect caused due to the movement of the peripheral zones of the billet close to the die and die holder surfaces, independent of the nonuniform flow in the container caused by friction, results in shearing. Material in the axis region flows more rapidly towards the die orifice than at the edge. A funnel-shaped hollow is thus formed in the rear portion of the billet [Pearson and Parkins, 1961]. A funnel can also occur in indirect extrusion [Thomsen et al., 1954], because shearing at the die is not prevented.

Pipe Formation, also called ***extrusion defect***, ***fishtailing***, or ***back-end defect***, is the most common flaw encountered during aluminum extrusion, especially in the 6xxx series alloys: an annular separation in the cross section (due to division into an inner core and an external zone) in the rear third of the extrusion. Billet-container friction results in the billet surface layers remaining stationary at the container wall while the billet core is sheared past. The region of dead metal that exists in the center directs the flow forwards giving rise to a cone shaped defect [Sheppard, 1999] as shown in Fig-3 (a-b).

Internal cracking is the development of cracks in the center of an extruded product. Also known as **centerburst**, **center cracking**, **arrowhead fracture**, or **chevron cracking** [Kalpakjian, 1997], these cracks are attributed to a state of *hydrostatic tensile stress* (also called *secondary tensile stress*) at the centerline of the deformation zone in the die. The situation is similar to the necked region in a uniaxial tensile test specimen.

Internal defects in hollow extrusions are produced due to friction between the mandrel and the internal billet surface, giving rise to a significant distortion of the material flow at the internal surface. The result is a blotchy, torn internal surface, and material welded to the mandrel is difficult to remove.

When lubricant traces are present in unlubricated extrusion or lubrication breaks down in lubricated extrusion, forming a partial dead metal zone, lubricant trapped at the boundary of the dead metal zone extrudes into the product to form **subsurface defects**. Upon subsequent heating, escaping gases cause blistering at these locations. These defects, close to the extrusion surface, result from the formation of **scales** or **blisters** and can develop in flow patterns of type *A* or *B*. Sometimes the blisters do not appear immediately after extrusion but during a subsequent heat treatment; Fig-4 (a) [Aluminum Association, 1993].

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3. SURFACE DEFECTS

Various defects mar the surface appearance of extrusion, including die lines, scoring, pick-up, and tearing. **Pick-up defect** is observed as intermittent **score lines** of varying lengths between 3 mm and 12 mm and often terminates in a fleck of aluminum debris referred to as *pick-up* deposit; Fig-4 (b). The problem is usually thought to be enhanced by inclusions in the cast billet, inadequate homogenization treatment [Langerweger, 1982] and die deflection. The defect is also temperature sensitive.

The Aluminum Association defines **die lines** as “longitudinal depressions or protrusions formed on the surface of the drawn or extruded material due to imperfections on the die surface”. Die lines, shown in Fig-5 (a), are also believed to be caused by the interaction of the die land area. Even with an optimum die land length and extrusion temperature, together with highly polished die lands, die lines are still observed to occur. These die lines are finer and shallower and are termed **micro die lines**.

4. WELD DEFECTS

It is now common practice to extrude billet on billet using a welding chamber or feeder ring to hold the back of the previous billet in the die and provide a surface for the next billet to weld on to. This can lead to defects known as *weld defects*. If the mating surfaces of the billets were perfectly clean, there would be no weld problem. In practice, the billet ends are always oxidized, and the sheared face is often contaminated by stray lubricant and oxidized metal from the shear blade. As a result the **billet-to-billet weld** or **transverse weld** is usually defective and represents a discontinuity in the extruded product; Fig-5 (b).

Whereas in a solid section the transverse weld merges into the section surface, in a hollow it also merges into the **longitudinal weld** line.

5. METALLURGICAL DEFECTS

Most of the metallurgical defects in aluminum extrusion can be divided into three major categories. **Streaking** defects on the surfaces of anodized extrusions consist of bands or lines appearing darker or lighter, brighter or duller, in color and tone than the remainder of the surface; Fig-6 (a, b). The basic cause of this streaking is a difference in microstructure between the streaked portion of the extrudate surface and the remainder, which leads to a difference in response in etching and anodizing [Cote et a., 1969].

Non-uniform appearance defects originate from occasional irregularities of the etching, anodizing and/or coloring processes. The two more important subcategories are hot spots and spangle. **Hot spots** characteristically appear as dark (gray or black) rough patches, at regular or random intervals along the extruded length. Originating due to localized coarse precipitation resulting from different cooling rates of adjacent parts of the section, **spangle** appears as a pronounced *grainy surface*. The cause of this defect is a preferential grain attack, visually emphasized by a *stepwise* appearance of adjacent grains owing to the dependence of the rate of attack on the orientation of the crystallographic planes of individual grains.

Silicon Marks are black burn marks formed on the section surface during extrusion due to inclusions of very hard particles such as Si or Mg in the billet material, creating very high local friction and temperatures.

6. DEFECTS RELATED TO TEMPERATURE AND SPEED

The onset of mill finish (no subsequent surface treatment) surface defects is related to the temperature rise generated at the surface of the product as it is deformed. The level of temperature rise increases rapidly with exit speed due to the greater rate of work input and reduced heat loss to tooling. At a high enough exit speed local melting might occur. This condition gives rise to the classic **hot shortness** or **U-shaped cracking** defect.

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 what is commonly called **fir-tree cracking** or **speed cracking** (circumferential surface cracks) as shown in Fig-6 (c).

7. EQUIPMENT AND TOOLING RELATED DEFECTS

The billet preheat ovens, billet shearing and transfer stations, die preheat ovens, extrusion press and die set, extrudate conveyors, and the post-extrusion correction stations, can all contribute to defects that can lead to rejection. Some of these equipment and tooling generated defects are briefly described below.

Black Lines are burnt surfaces on the extrudate due to a local high pressure in the extrusion press; Fig-7. 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.

Nonuniform heating in any of the billet preheat ovens (due to local malfunction, deposits, etc) can cause localized high temperatures. The resulting alloy segregation may cause streaks of pure (whitish) aluminum in certain locations, appearing as **white lines** after extrusion.

Runout marks, also called **graphite lines**, appear on the extruded surface (especially for heavy sections) due to friction of the hot section against conveyor rollers made of graphite; Fig-8 (a).
Whenever, due to a malfunction of a furnace or press component, the extrusion is temporarily stopped, **die stop marks** are formed on that particular section; Fig-8 (b).

Stains/oil patches are formed when oil splashes during saw cutting (to get required section lengths after extrusion) spread on the extruded sections and burn because of high temperature; Fig-9 (a). These stains can further deteriorate in the aging furnaces.

Several factors can cause dissimilar metal flow in the cavities of a multi-hole die, resulting in **bending or twisting**; Fig-9 (b). Similar problems can arise if the billet is not uniformly heated on all sides, resulting in a nonuniform temperature distribution. Some bending can also occur due to improper support during stacking.

If the die surface is not smooth enough (due to wear, lack of hardness, hard inclusions on die surface) or if the conveyor belts are damaged, **scratches** might appear on the extruded surface. There can also be general **damages** such as ends not being smoothly cut off by saw cutting, or sections being damaged by falling down or collision during movement by overhead cranes, etc. Damages can also occur during the stretching/straightening and roll correction stages; Fig-10 (a). **Dents,** as shown in Fig-10 (b), can occur during transferring long extruded sections from one place to another by moving rollers or overhead-cranes.

In multicavity dies, extruded sections may rub against each other while coming out of the die openings. This chafing of hot extruded sections crates **hot rub marks**. Whenever the surface quality is below a specified industry standard, due to excessive die lines or any other surface problem, the unacceptable defect is termed **rough surface**.

The extrusion industry has various standards prescribing dimensional tolerances for acceptable architectural and other extruded products. 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 **convex** or **uneven surface** is another die related problem. It can also occur due to over-stretching of a critical surface in the correction area. 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.

As-extruded aluminum is quite soft and is therefore heat-treated by age hardening in furnaces for prescribed temperature-time cycles depending on the aluminum alloy. Due to any number of malfunctions or problems in the furnaces, the aging process may produce **low hardness**.

8. ANODIZING DEFECTS

When there are small contaminations in the water in rinse tanks, and the sections are left immersed for more time than necessary, small local corrosion spots called **black pits** are formed. **Corrosion** can sometimes happen due to damp or salty atmosphere, especially in certain geographical locations. Fig-11 (a) shows a surface marred by pitting and corrosion. When the sections are left in the caustic/etching tanks longer than required, a more than optimal surface layer is removed. The result is a grainy appearance, giving a **dull finish**. If sections are left too long without rinsing after the caustic tanks, the caustic solution sticks locally and does not come off after rinsing, giving rise to **caustic patches**.

Sometimes, when the anodizing quality is not good after completion of the process, the whole cycle has to be repeated. This repeated etching can result in more material removal than permitted. The result has to be scrapped due to **reduced wall thickness**. If the etching/anodizing cycle is to be repeated, may be several times, the previous anodizing layer has to be removed. If this is not done correctly, then there is **nonuniform etching** that leads to rejection.

Process scrap is the name given to miscellaneous rejects due to bad clamping resulting in sections falling into tanks, or falling down and bending/twisting, or dents and damages during handling and transportation.

9. PAINTING DEFECTS

If any of the painting parameters (such as current, pressure, and nozzle size) are inappropriately set, or due to a combination of these, there can be an insufficient layer of paint called **less microns**.

Dust Particles can obviously give an unacceptable painting quality and appearance. Reasons might be contaminated paint powder, or dust particles in the painting oven.

An improper current or pressure setting can have the consequence of more powder in certain locations. This leads to a porous appearance very much like the skin of an orange having minute projections and depressions. This **orange peel** defect is shown in Fig-11(b).

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If **blisters** caused during extrusion are not removed before painting, or if they become visible only after anodizing/painting, the only usual recourse is scrapping the product.

Due to currents of hot air in the oven, two sections might sometimes collide and stick together, creating **overlapping** defect. After drying off, they cannot be pried apart without excessive damage and are thus scrapped.

10. RECOMMENDED PREVENTIVE AND CORRECTIVE MEASURES

Some of the defects described above cannot be avoided due to the nature of the process and existing circumstances. However, as most of the flaws originate in controllable process and tooling features, they can either be prevented or mitigated. As the mechanics of most of the flaws is not very clear, majority of the following recommendations are heuristic in nature, based on tried and tested industrial practice.

A **funnel** defect can extend into the rear of the extrusion; hence, the billet should not be extruded completely. The optimum length of the discard must be determined experimentally and must be greater for lower extrusion ratios (as in the production of thick rods), because the defect develops at an earlier stage.

One or more of the following methods can be used to reduce the **pipe/extrusion** defect:

(a) *Extrusion with a shell*: This method is based on keeping the diameter of the dummy block 3 to 5 mm less than that of the container. The shell sheared off by the dummy block during extrusion remains, together with all impurities, as a cylinder and is pushed out after each extrusion.

(b) *Machined billets*: Surface impurities and oxide skins can be removed to a certain extent by machining off the dirty, uneven, as-cast surface of the billet.

(c) *Extrusion with a long discard*: A successful but expensive method, it involves interrupting the process before the defect appears, leaving a correspondingly large discard.

(d) *Similar billet and container temperatures*: When type *C* flow is caused by a temperature gradient resulting in heterogeneous deformation, altering the container temperature to that of the billet can reduce or prevent the danger of pipe formation.

To avoid **internal defects in hollow extrusion**, a lubricant can be used to improve the flow, helping to obtain a better inner surface. In many cases, however, a lubricant is dangerous, because it can easily be trapped under the tube surface during extrusion, resulting in blistering at high temperatures.

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There are three possible ways to prevent **scales and blisters**:

(a) *Extrusion without a lubricant and with a flat die* not only removes the possibility of lubricant inclusions but also increases friction between the billet and the container. This restricts the billet surface along the container wall to such an extent that it cannot flow into the extrusion. The material therefore flows beneath the surface of the billet by shearing and the residual surface layer containing the impurities collect in front of the dummy block.

(b) *Extrusion with a shell*: If scales and blisters still appear even when no lubricant is used, extrusion with a shell (method described above to prevent pipe formation) can be used.

(c) *Extrusion with a lubricant and with a conical die*: An alternative approach is to reduce the dead metal zone to such an extent that there is virtually no possibility of billet surface flowing into the extrusion. This can be done by using a good lubricant in the container and on the die, resulting in flow type *S* or *A*. Use of conical dies further increases the desired homogeneity of flow.

(d) To avoid air entrapment during upsetting, a *burp cycle* is often employed, removing the ram pressure momentarily after upsetting to allow the air to escape.

Apart from improved casting procedures and homogenization practices, attempts at eliminating **pick-up** defect have focused on modifications to tooling and improved extrusion practices including die modifications by nitriding, use of die materials less prone to aluminum build up, employment of an inert atmosphere [Kobayashi and Okinawa, 1977], and the use of die cooling [Bischel et al., 1981].

There is a minimum die land length for successful surface operation (least visible **die lines**). At this optimum condition the entire land length is choked, preventing the introduction of oxygen to the virgin surface. The result is prevention of an oxide film that generally scores the surface. Polishing the die land is also an improving factor.

If dies are designed in such a way that the welds occur on non-visible surfaces in the finished product, **weld defect** can be minimized.

Die-design streaks and **weld streaks** cannot be generally removed by mechanical treatment of the section. However, a discard of appropriate dimensions normally eliminates extrusion-defect streaks. Similarly, **hot spots** cannot be generally eliminated after they have formed. The only possible solution is to avoid contact between the hot extrusions and the run-out table for more than the shortest time. Also, the defect called **silicon marks** is related to billet composition, which is very difficult to control; since the problem is rare, defective parts of this type are scrapped.

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Temperature and speed related defects can obviously be avoided by using lower temperatures and speeds (thus reducing the strain rate). However, this would slow down the output and reduce productivity.

Runout marks may disappear (if not too dark) during anodizing and painting. Otherwise, graphite rollers must be properly maintained or replaced after optimum service life. As **die stop** marks cannot be removed once formed, the portion including the mark is discarded. To avoid **stains and oil patches**, the saw should optimally be placed far enough from the press to give extruded sections time to cool down so the oil will not burn.

For prevention of **twists and bends**, die cavities should be properly centered to obtain equal metal flow for all sections. Sometimes, if desired symmetry is unattainable, an additional cavity can be introduced. Also, minor bending/twisting can be corrected on the *stretching* machine. For avoiding **dents** care must be taken during conveyor and overhead-crane transport as well as during packing. Defective parts of this type are few and have to be scrapped.

Preventive measure against **scratches** is periodic cleaning, polishing and nitriding of the die surfaces. Beyond a certain amount of surface erosion, the die should be replaced. **Hot rub marks** can be prevented by the use of separators (generally graphite blocks) placed upstream of the multi-cavity die to make sure that no contact or rubbing takes place between the exiting sections.

If not beyond repair, **out of angle** defect can be removed on the *roll correction* machine. To avoid **uneven wall thickness**, the extrusion process must be stopped and the mandrel must be re-aligned properly.

11. IMPACT ON OPERATIONAL COST

All of the defects described above lead to production losses, either reflecting the cost of rework or of scrap. Here, we are concerned with defects resulting in complete rejection of the extruded sections, which are then taken back to the remelting shop. This locally recycled aluminum is obviously not premium grade and can be used only for noncritical applications. For any evaluation of plant productivity and efficiency, it is therefore necessary to be able to quantify these losses.

11.1 Defect Cost Breakdown

It will be practically almost impossible to treat each defect separately in building up a workable cost model. As already described above, classification of these defects into categories with similar attributes facilitates a much better understanding of their causes and remedies. However, for a cost analysis, the taxonomy (based on mechanics and metallurgy) depicted above is not very suitable.

Actual rejection data from a local extrusion setup, spanning a period of ten years, was collected and tabulated. Table-1 shows a one-year sample of the reject amounts (tons of product) due to various unacceptable defects. The categorization into three major **cost centers** (press, anodizing, and painting) is typically employed by the industry and lends itself nicely to cost breakdown and modeling. Figure- 12 is a graphical comparison of the total extruded product that was rejected each year in each cost category (each major production stage) during the period from 1992 to 2000. The trend of rejection costs over the years in each cost center is depicted in Fig-13.

11.2 Defect Cost Model

The cost model proposed below works in a generalized framework, incorporating the probabilities of producing a defective part at each stage, as shown in Fig-14. It should be pointed out here that the first three stages are grouped into a single cost center (Press Defects).

If we have

P_i = Fraction (probability) of defectives at different stages, (i= 1, 2, 3, 4a or 4b) and

C_i = Individual cost of different stages,

then the *Ideal Total Cost Per Ton* of the final product (no defectives at any stage) would be

$$T_{CI} = \sum_i C_i \, .$$

The *Actual Total Cost per Ton* of the final product (considering fraction of defectives at each stage) would be

$$\begin{aligned} T_{CA} = {} & C_1 + P_1C_1 + C_2(1-P_1) + P_2(1-P_1)(C_1+C_2) \\ & + C_3(1-P_1)(1-P_2) + P_3(1-P_1)(1-P_2)(C_1+C_2+C_3) \\ & + C_4(1-P_1)(1-P_2)(1-P_3) + XP_4(1-P_1)(1-P_2)(1-P_3)(C_1+C_2+C_3+C_4) \\ & + (1-X)P_5(1-P_1)(1-P_2)(1-P_3)(C_1+C_2+C_3+C_4+C_5) \end{aligned}$$

In a compact form, we have

$$T_{CA} = C_1 + P_1 + \beta \sum_{i=2}^{n} \left[C_i \left[\prod_{j=1}^{i-1} \left(1 - P_j\right) \right] + P_i \left[\prod_{j=1}^{i-1} \left(1 - P_j\right) \sum_i C_i \right] \right],$$

where β equals x for stage 4a and (1-x) for stage 4b; for all other stages β is 1.

Based on these two costs, we can easily find

$$\textit{Plant Efficiency} = \frac{T_{CA}}{T_{CI}} \, .$$

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12. CONCLUSIONS

All the defects typically encountered in the industry have been defined and explained with visual illustrations. Flaws are categorized into metal-flow related, surface, weld, metallurgical, temperature and speed related, equipment and tooling related, anodizing, and painting defects. Causes and mechanisms of defect formation are discussed on the basis of mechanics and metallurgy in most of the cases. Various defects, categories, and mechanisms have been described that are not hitherto reported in literature. Real world rejection data from local extrusion industry, covering a period of ten years, has been collected, classified, and tabulated. A generalized model has been developed for cost analysis of any commercial extrusion setup, easily adaptable to other hot metal forming process.

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Table-1 Typical annual defects data (in kg) from an extrusion industry, classified into three cost centers

PRESS DEFECTS		Anodizing Defects		Painting Defects	
Black/White Lines	137571	Black pits	41540	Less Micron	33741
Scratches/Damages	86075	Dull Finish	2495	Dust Particles/Orange Peel	20354
Other Defects	19441	Corrosion	9685	Blisters/Overlapping	1080
Stain/Oil Patches	14807	Process Scrap	37102	Damages/Scratches	387
Silicon Marks	14799	Caustic Patches	5936	Others	39448
Blisters/Die Stop	11261	Fallen in Tank	3438	Total Rejection	95010
Low Hardness	11196	Wall Thickness Reduced	8286	Total Painting output	1532419
Concave/Convex	11180	Damaged/Scratches	41288	% of Internal Rejection	6.20
Twist/Bends	9202	Total Rejection	149770		
Graphite / Runout Mark	4809	Total Anodizing Output	10051677		
Out of Angle	1311	% of Internal Rejection	1.49		
Off Dimension	959				
Rough Surface./B. Hole	0				
Total Internal Rejection	322611				
Total Production	17069365				
% of Rejection	1.89				

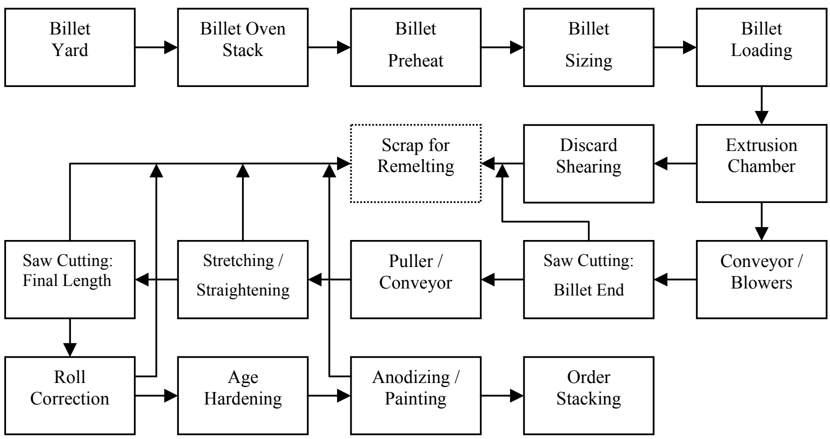

Figure-1 Process flow in commercial hot extrusion of Al-6063 [Arif et al., 2001]

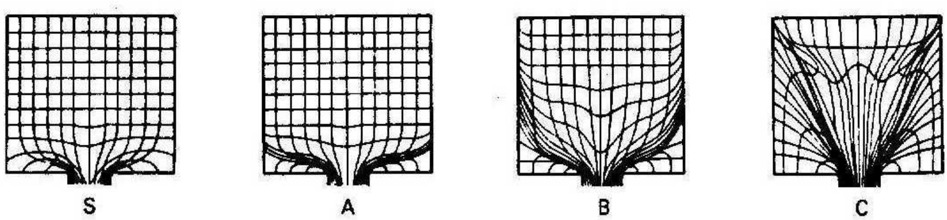

Figure-2 The four different metal-flow types in extrusion shown schematically [Laue and Stenger, 1981]

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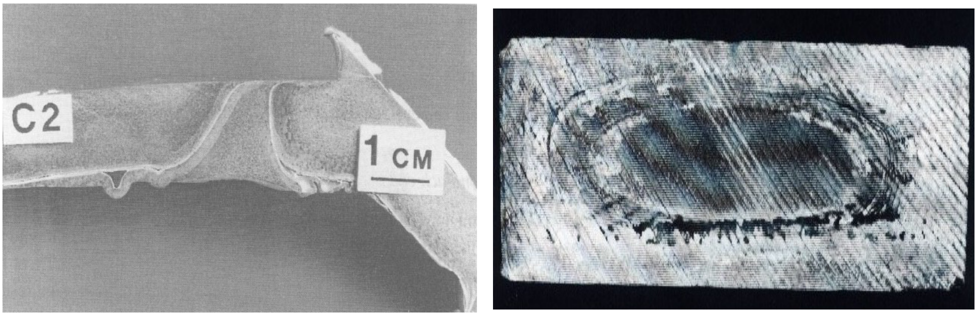
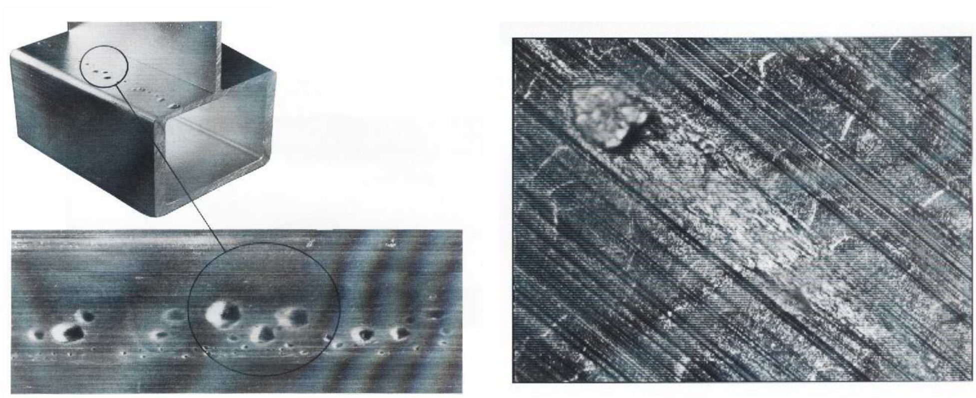


(a) (b)

Figure-3 Pipe or extrusion defect, also known as back-end condition [Sheppard, 1999].



(a) (b)

Figure-4 Blisters (a) and pick-up (b) are surface defects [Aluminum Association, 1993].

(a) (b)

Figure-5 A die line (a) is a longitudinal depression or protrusion formed on the extruded surface, while a weld line (b) may be due to an imperfect billet-to-billet joint.

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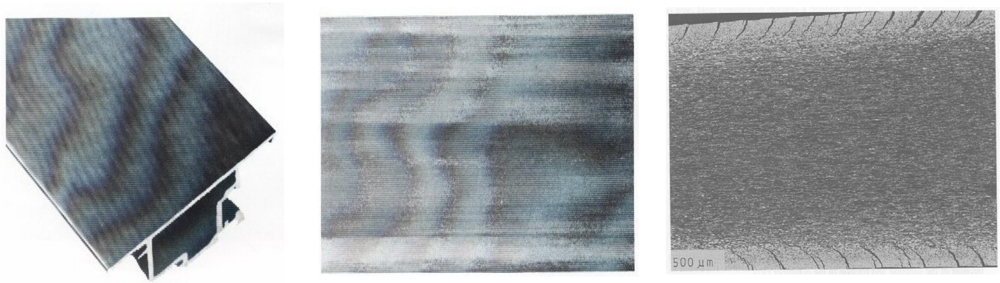


(a) (b) (c)

Figure-6 Surface appearance due to die design or bearing streaking (a), ingot (billet) structure streaking (b), and surface cracking / tearing (c) [Aluminum Association 1993, Sheppard 1999].

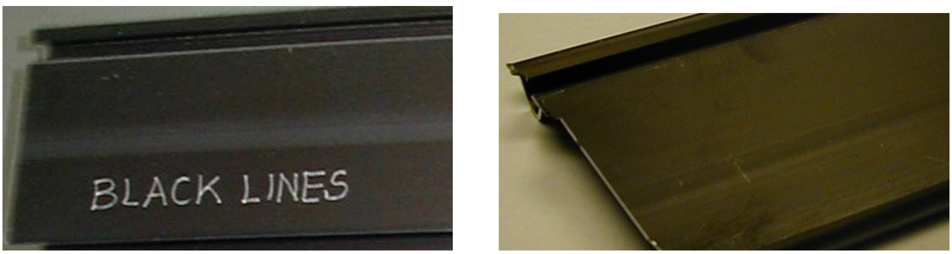
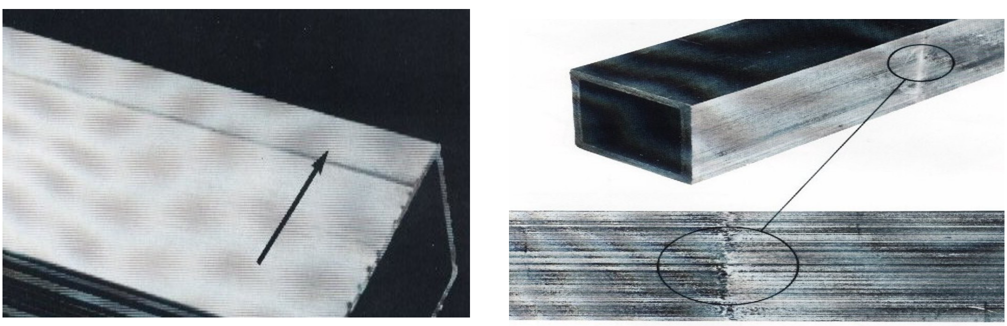


Figure-7 Black lines show as burnt surfaces on the extrudate due to local high pressures/temperatures.



(a) (b)

Figure-8 Runout marks (a) are usually longitudinal and can be either *carbon marks* or *roll marks*, while a stop mark (b) is a band-like pattern perpendicular to the extruded length [Aluminum Association, 1993].

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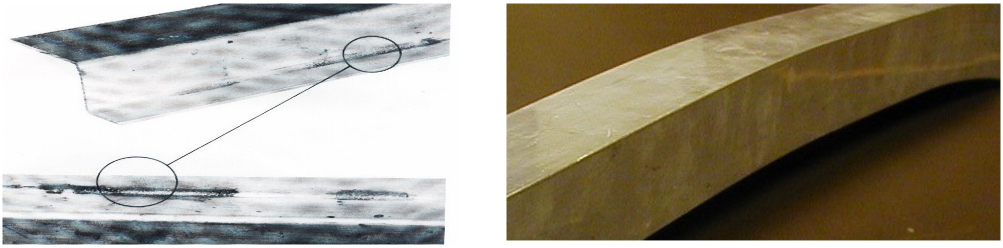
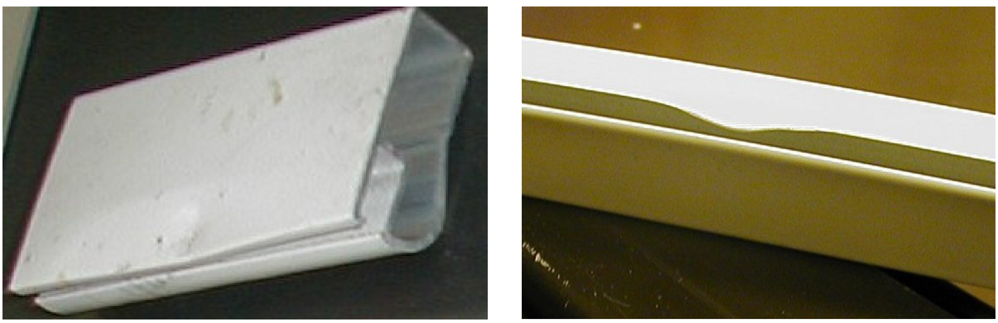


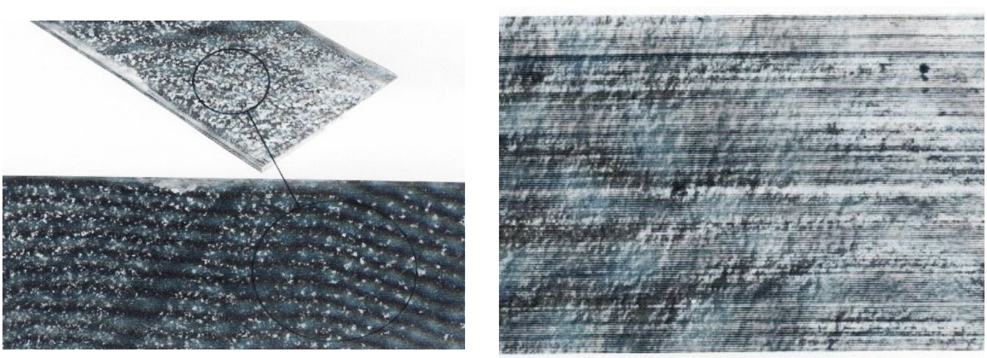
(a) (b)

Figure-9 Stains/oil patches (a) show as a yellow to brown area of surface discoloration, while twists and bends (b) occur due to a winding departure from straightness.



(a) (b)

Figure-10 Damages (a) and dents (b) are categories of handling and traffic defects.



(a) (b)

Figure-11 Pitting corrosion (a) is caused by chemical/electrochemical reaction, while orange peel (b) is a rough surface texture associated with large grains in the metal [Aluminum Association, 1993].

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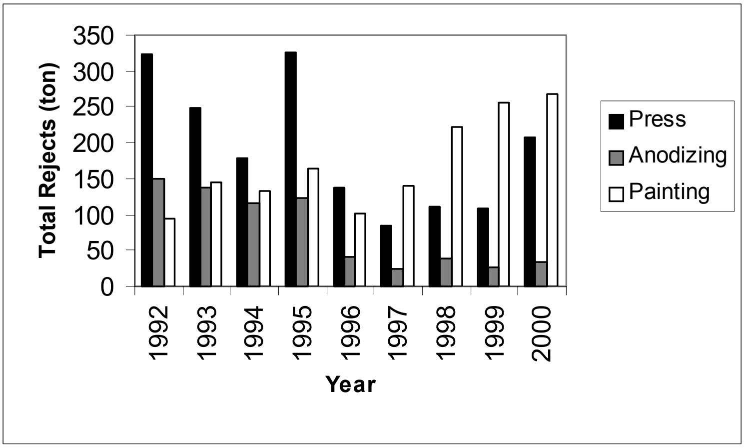

Figure 12 Comparison of rejects at the three cost centers over a 10-year period.

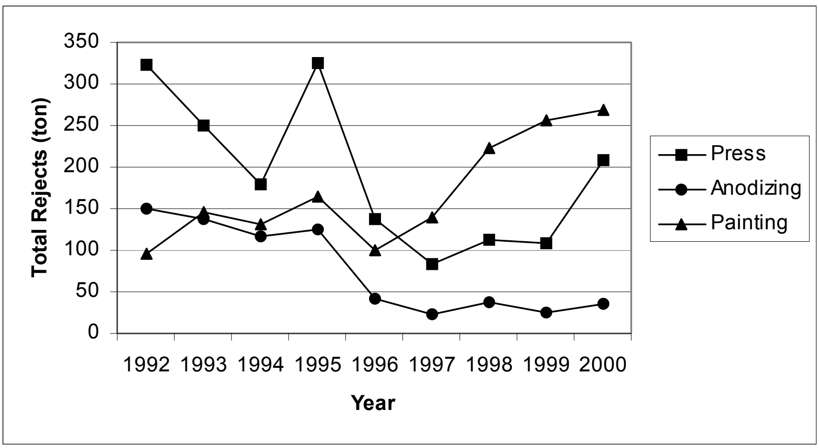

Figure-13 Total rejections in metric tons at each cost center (press, anodizing, painting) over a 10-year period.

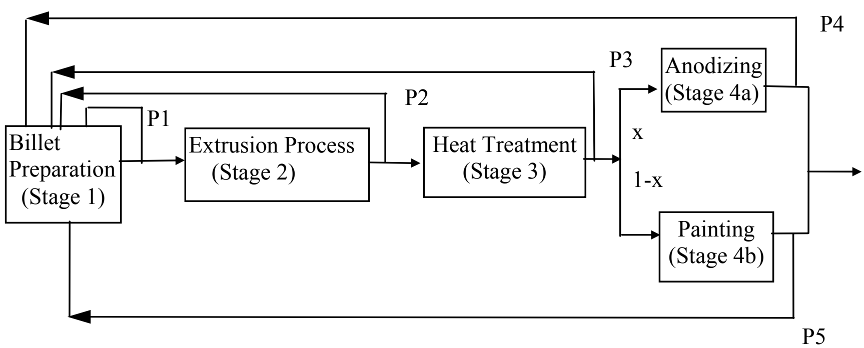

Figure-14 Plant layout showing cost centers and fraction of defectives at each stage