CONTROLLING THE FEATURE ANGULARITY OF EXTRUDED ALUMINUM PRODUCTS: AN EFFICIENT METHODOLOGY FOR MANUFACTURING PROCESS IMPROVEMENT

by

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Submitted to the MIT Sloan School of Management and to the Department of Mechanical Engineering in Partial Fulfillment of the Requirements for the Degrees of

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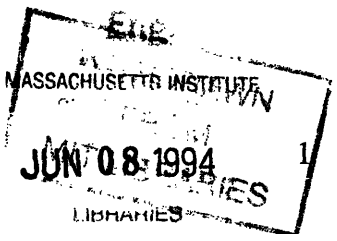

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in Conjunction with the Leaders for Manufacturing Program

Abstract

This study examines the concept of the efficiency of resource usage in the practice of manufacturing process improvement. A strategy for increasing the efficiency of process improvement projects was formulated and tested in an industrial setting. The resulting framework is offered as one example of a process improvement methodology which was designed with the efficient use of resources as an explicit goal.

The methodology that was developed is comprised of three overlapping phases: a data survey, an analytical study, and a series of designed experiments. Gains in efficiency come from an emphasis on strategic pre-project planning and from synergies which result from the real-time integration of data produced by the three phases of the methodology. The result of the methodology is a proven "mental model" which describes the relationships between important process parameters and the quality of the final product, and is subsequently used to generate and evaluate ideas for process improvement. In addition, the mental model can have long-term benefits if it is further developed, refined, and integrated into the facility's decision-making processes.

A process improvement project was conducted at an aluminum extrusion facility and is offered here as a case study of the methodology. The goal of the project was to improve the extruder's ability to hold tight tolerances for feature angularity in extruded aluminum aircraft parts. The mental model which resulted was used to identify modifications to the facility's standard die design which reduced the variation in feature angularity by over 50%.

Thesis Advisors:
Professor Stuart B. Brown, Richard P. Simmons Professor of Materials Manufacturing
Professor Roy E. Welsch, Professor of Management

Acknowledgments

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Finally, I want to thank Rebecca, my wonderful wife, whose unwavering support, sense of adventure, and amazing blueberry pies made this internship great fun!

Table of Contents

List of Charts and Diagrams

Chapter 1: Introduction

Innovation cannot occur except in the presence of slack.
-March and Simon, Organizations

In my opinion, the most glaring and significant shortcoming of Western management today is the lack of improvement philosophy.
Masaaki Imai, Kaizen

The Process Improvement Paradox

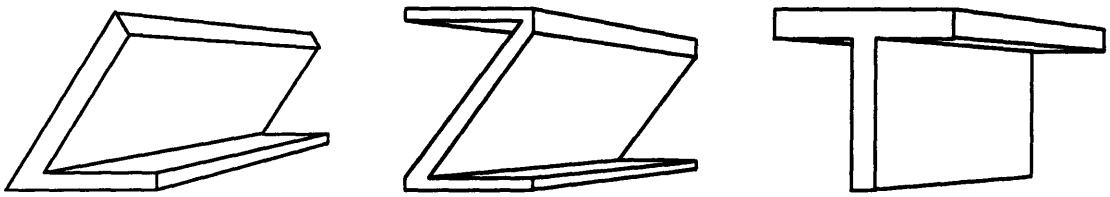
Modern American manufacturers are faced with a paradox. Increased competitive pressures at home and abroad have forced them to become lean, rethinking production techniques, slashing inventory, and eliminating "waste" in the name of efficiency. Initially, opportunities for process improvement abound. Gains are relatively easy as many operations have not been seriously examined for years. Sooner or later, however, diminishing marginal returns set in and further improvements become very difficult. At this stage, when making improvements is most difficult, would-be process improvers are faced with the dilemma of having fewer resources with which to work. The personnel and equipment that were shed in "right sizing" exercises are now unavailable for performing experiments or collecting data. Furthermore, the workers that remain have less time for process improvement activities, as more of their attention is now devoted to meeting production goals. In spite of the ubiquitous "Continuous Improvement" slogans, the drive for efficiency has stripped many manufacturing organizations of the resources they need to make further gains.

This study examines the concept of efficiency of resource usage in the practice of process improvement. A strategy for increasing the efficiency of process improvement projects was formulated, then tested in an industrial setting (an aluminum extrusion facility

referred to in this document as "the Plant", which is operated by "The Company"). The resulting framework is offered as one example of a process improvement methodology which was designed with the efficient use of resources as an explicit goal.

The Problem

Extruded products are unique in that they have constant cross-sectional geometries along their lengths. In the aerospace market, several typical shapes make up a large percentage of aluminum extrusion production. These shapes are angles, zees, and tees (see Figure 1).



angle zee tee

Figure 1. Typical Shapes of Aerospace Extrusions

These parts, which can be over 20 feet long, are incorporated into aircraft by airframe builders. At the assembly stage, fit and finish is crucial. Feature angularity, defined as the angle between adjacent features (e.g., the angle between the stem and cap of a tee), is of particular importance to airframe builders. If an extrusion does not mate with adjoining parts in accordance with the engineering design, the parts must be "shimmed", or, basically, wedged into their mating positions. This is done with the use of

aluminum wedges and spacers and with costly production tooling. Rework of this type is extremely expensive for the assembler, who must employ highly skilled workers to finesse the ill-fitting members into position. The magnitude and significance of this problem becomes apparent when one considers that a Boeing 747 has in excess of 4 million individual parts (including fasteners). One domestic airframe builder has spent an estimated $ 9M per year on labor alone to rework seat track extrusions for a single airliner program.

Angularity problems translate into higher costs for end-users as well. The shims and spacers which are added to correct angularity problems add weight to the airframe, reducing fuel economy and cargo-carrying capabilities for common carriers. One estimate places the weight of such remedial fixtures at over 1000 lbs. on a typical 747, a nontrivial amount. The resulting reduction in efficiency and performance will, of course, endure throughout the entire life of the airframe, a period of 20 years or more.

To combat these problems, domestic airframe builders are pushing the aluminum extrusion industry to increase the geometric accuracy of extrusions beyond the published industry standards. The Aluminum Association guidelines for angularity are listed as nominal ± 1.0°, 1.5°, or 2.0°, depending on the wall thickness and aspect ratio (length/thickness) of the feature in question. Recent orders suggest that aerospace extrusion customers may begin requesting tolerances on angularity of nominal ± .5°, or, perhaps even ± .25°, on a routine basis in the near future. This development formed the impetus for the process improvement project described by this thesis. It is hoped that improving the Company's ability to control critical angles will translate into a strategic advantage in the competitive market for aluminum aerospace extrusions.

The Methodology

The goals of this study were to explore ways of using process improvement resources more efficiently, and to develop concrete recommendations for improving The Company's ability to control critical angles. To achieve these goals, a process improvement methodology was designed and tested at the Plant.

The author of this document hopes that the recommendations offered herein will be of lasting value to the Plant, but perhaps more importantly that the description of the successes and failures of the process improvement methodology and the project itself will serve as a useful guide for process improvement practitioners at the Plant and elsewhere.

Planning

In conducting the pre-project planning for this study, particular care was taken to design efficiency into the process improvement methodology. Specifically, the methodology attempted to utilize available resources as efficiently as possible. With this goal in mind, the following general guidelines were established:

- be realistic in assessing what resources are available for the project,
- apply resources where they will yield the greatest benefit,
- know when to end each step in the project and move on, and
- make full use of synergies between different parts of the project.

Structure

The methodology that resulted consists of three phases: a data survey, an analytical study, and an experimentation phase. This structure seemed logical since it corresponds to the three generic questions that most process improvement projects seek

to answer: How is the process currently performing? What process variables drive product quality? And what can be done to improve product quality? Figure 2, below, illustrates the relationship between the three phases; each phase overlaps with and builds upon the preceding phase.

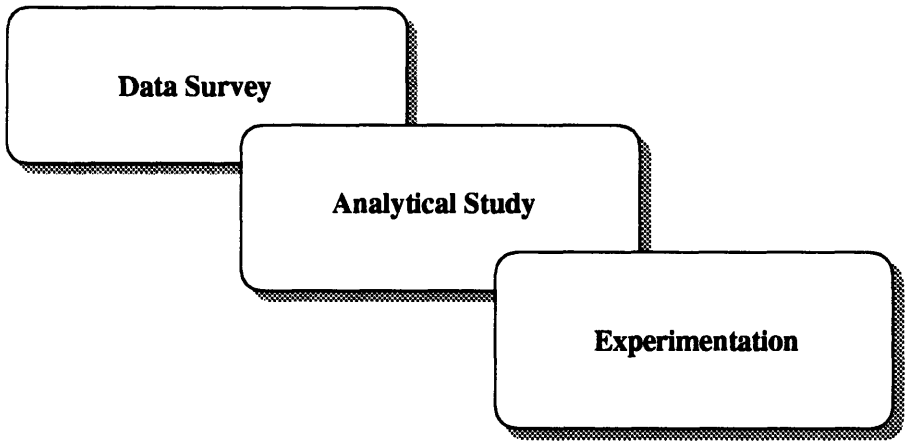


Figure 2. Three Phases of Process Improvement

Resource Allocation

This process improvement methodology requires the practitioner to list the resources that will be invested in each phase. This is done to encourage the thoughtful identification and allocation of available resources. It also provides an occasion for the planner to ration scarce resources (e.g., the practitioner's time) by investing more of them in the phase(s) in which they will yield the greatest benefit and less of them where the benefit is small. This resource allocation step may also aid in the identification of tradeoffs that can be made to improve overall efficiency. This is made possible by the fact that a weakness in one phase may often be addressed by strengthening one or both of the other

phases. For example, if data is unreasonably difficult or expensive to collect, a process improvement practitioner may choose to invest fewer resources on the data survey, compensating instead by spending additional time performing a more thorough analytical study or running additional experiments. Efficiency can be increased in this way if the time that is shifted out of the data survey will yield greater benefits if it were to be invested in one of the other phases than if it were to be used merely to collect a few more data points. The general rule-of-thumb here is to maximize the benefit of each unit of resources by investing it in the phase of the project in which it will yield the greatest return.

Intermediate Goals

This methodology also includes a list of questions which are to be answered at each phase of the project . This is done to provide both a clear goal for the phase and a yardstick with which to measure progress. When the questions are answered sufficiently, the phase is declared to be complete so that resources can be reallocated to the next phase without delay. A summary of the project plan for this study is shown in Figure 3, below. Note that the questions that were listed are detailed enough to give direction, but are not specific to the point of becoming leading or constrictive. This is important because process improvement projects should attempt to uncover truth, not steer results to predetermined conclusions.

Synergy

Synergy is defined as the condition in which a whole is greater that the sum of its parts. Synergy can be achieved between the phases of the process improvement methodology if one is careful to apply the knowledge obtained in each phase to the other

phases. This is done in practice by overlapping the phases of the project and utilizing all available information in making each decision. In this way, one can use preliminary results from earlier phases to avoid investing resources to investigate factors which are of lesser importance, thereby promoting the efficient use of resources. Information can also be passed from later phases to earlier phases since they are overlapped. The key to creating synergy between the phases is to avoid following a rigid project schedule. It is better to allow each phase to develop naturally by continually revising the details of the plan as additional information becomes available.

Phase	Resources	Questions
Data Survey	**3 person months** **digital protractor**	**What are our current capabilities?** **What processes cause variation?** **What geometric/metallurgical factors influence variation?**
Analytical Study	**1 person month** **trade publications** **technical ability**	**How should we think about the distortion of angularity?** **What are the root causes of variation in angularity?**
Experimentation	**2 person months** **statistical knowledge** **raw material** **press time**	**Is our mental model "correct"?** **How will variation in angularity change if we _____?**
All Phases	**MIT advisors** **experienced coworkers**	

Figure 3. Resources and Questions

Constructing a good project plan requires a blend of structure and flexibility. Structure is needed to keep the project on course, and flexibility is needed to provide the freedom to take advantage of developments and opportunities that cannot be foreseen at the outset. This approach can cause anxiety for technically trained individuals who favor clearly defined tasks and objectives. One must keep in mind, however, that it is the flexibility of the methodology which boosts efficiency.

Chapter 2: Extrusion Processing

Industry Overview

The first aluminum extrusion press in North America was opened by Alcoa in New Kensington, PA, in 1904. Since then, the North American aluminum extrusion industry has grown to include 80 extruders operating 140 plants with some 390 presses. In the 1980s, extrusions accounted for an average 19.5% share of aluminum mill products shipped to end-users and distributors [Purchasing, 1992, p. 68B4].

The Company specializes in the extrusion of 2xxx and 7xxx series aluminum alloys, commonly referred to as "hard alloys". Hard alloys are more difficult to extrude but provide greater strength than the softer aluminum alloys. As such, hard alloy extrusions command a premium price and are used in industries which require light, high strength parts, such as aircraft manufacturing. Aerospace firms often prefer extrusions over machined or stamped parts because they can be produced to net shape, requiring little or no additional processing, and can be manufactured to fairly tight tolerances. The aerospace segment of the hard alloy aluminum extrusion market is highly prized by extruders for its high margins. The Company has historically competed in this niche. While its reputation for quality and on-time delivery performance have enabled it to win a healthy share of the market, it is now experiencing increasing pressure from customers and competitors.

The Company's aerospace customers have been hurt by recent reductions in the U.S. defense budget, the recent drop in orders from the embattled domestic airline industry, and by increased foreign competition, notably from the European Airbus consortium. They have responded to these pressures by looking for ways to cut costs and simplify their assembly processes. As the market for aerospace extrusions has shrunk, competition among hard alloy extruders has increased. Extrusion industry publications

indicate a widespread movement toward Total Quality Management principles and the tighter control of manufacturing processes. The Company has responded to these developments by reducing costs and initiating quality improvement programs of its own.

Process Overview

The Extrusion Process

Extrusion is an extremely flexible manufacturing process. Materials from plastic to steel may be extruded into surprisingly complex cross-sectional geometries (referred to as "shapes") by forcing cylindrical billets of material through a die. The product which emerges, called an extrudate, has, in principle, a constant cross-sectional geometry along its length. The flexibility of extrusion comes from the fact that a single extrusion press may be used for multiple materials and can produce an infinite number of shapes by simply changing the die and the associated tooling. Thus, a myriad of products may be produced with few or no modifications to equipment.

There are two main types of extrusion: direct and indirect. While both methods involve forcing a billet of material through a die, the difference lies in whether the die or the billet is held stationary. Direct extrusion is characterized by pushing a billet against a stationary die. Indirect extrusion, on the other hand, is performed by forcing the die over a stationary billet.

Indirect extrusion generally provides greater front-to-back dimensional control over the final product since the absence of friction between the billet and the container wall results in an extrusion cycle that more closely resembles a steady state process (i.e. constant exit temperature, extrusion load, and material flow patterns within the billet). Indirect extrusion, however, cannot match the productivity rates of direct extrusion due to

the long dead cycle times which are necessary for removing the "shell" (the skin of the billet), from the container at the end of the cycle and the greater complexity of indirect extrusion tooling [Laue, 1976, pp. 75-78]. Economics, therefore, dictate that most aluminum extrusions are produced by direct extrusion. Dimensional inaccuracies are dealt with by making slight modifications to the die (referred to as "repairing the die") or by passing the extrusions through subsequent rework operations. This study concentrated exclusively on direct extrusion production.

A cross-section of a typical direct extrusion press is shown schematically in Figure 4. It consists of the following basic components:

Container - a hollow steel cylinder which holds the billet as it is compressed

Die - a steel disc with a hole machined through it that molds the extrudate

Ram - a heavy steel rod which drives the billet against the die

Dummy Block - a steel disc which isolates the ram from the billet.

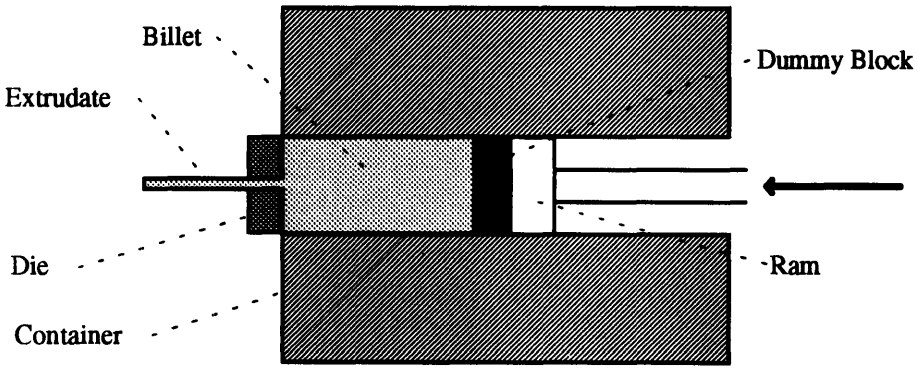


Figure 4. Direct Extrusion Press Schematic

The extrusion cycle begins when a preheated billet is loaded into the container. A dummy block is then inserted behind the billet. The dummy block creates a seal against the container wall so that billet material cannot squeeze past and prevent the ram from retracting when the forward stroke is completed. The dummy block is driven forward by the ram, compressing the billet which deforms to take the shape of the container cavity. As additional force is applied by the ram, stresses build within the billet, causing local plastic deformation in accordance with the Von Mises yield criterion[1]. At this point, billet material is forced through the die opening to form the extrudate. The geometry of the die opening determines the cross-sectional geometry of the extrudate. The ram will continue to travel until approximately one inch of billet material is left in the container. At this time, the motion of the ram stops, then reverses as the ram is pulled from the container. The extrudate is sheared off, and the remaining billet material (called "butt") and the dummy block are quickly ejected from the container. The press is now ready to receive the next billet.

Finishing Processes

Extrusion is only the first step in the manufacturing process. Subsequent finishing processes are necessary to achieve desired mechanical and metallurgical properties, correct geometric flaws, and prepare the extruded pieces for shipment. Few lots pass through all of the finishing processes. The routing a lot will take is determined by the desired temper and the results of in-process quality inspections. The material flows in extrusion facilities are similar to those of a job shop.

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[1] $\sigma = (1/\sqrt{2})[(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2]^{1/2} = \sqrt{3}k$ at the onset of plastic deformation, assuming isotropic deformation (k = shear strength)

Rough cut is the processing step which removes the distorted front and back ends from the extrusion. This is performed at the press with a cutting torch.

Heat Treat is a thermal process which is used to increase the mechanical strength of the aluminum through a heat/quench cycle. Extrusions are hung vertically in a natural gas-fired heating tower. When the desired heating profile has been achieved (placing alloying elements in solution) the extrusions are rapidly cooled by quickly lowering them into a pit that contains a mixture of water and glycol.

Age is a thermal process which is designed to further increase the hardness of heat treated metal by facilitating the precipitation of alloying elements, namely zinc, copper, and/or manganese. It is achieved by holding the metal at an elevated temperature for a specific length of time in order to speed up the precipitation hardening that occurs naturally at room temperature.

Anneal is a thermal process which is used to soften metal by removing the strain hardening that occurs during extrusion. It is similar to the Age process in that the metal is heated to a specific temperature for a specific length of time, then cooled in a controlled manner.

Stretch is a mechanical process that is used to straighten extrusions. Every extrusion is stretched before it is shipped. The extrusion is gripped at each end by steel jaws, placed in tension by a hydraulic press, and elongated a predetermined amount. The stretch operation is sometimes used to bring cross-section dimensions which are over top tolerance into tolerance.

Finish Cut is typically performed after stretch with a circular saw to reduce the length of the extrusion to the ordered length.

Roll is a rework operation that is used to restore flatness to an extruded feature or to adjust the gap between two points on a complex cross-section (for example, the tips on a part with a C-shaped cross-section). The extrusion is passed between rotating rollers that have been adjusted to place pressure on the extrusion at specific locations.

Detwist is a rework operation which involves visually inspecting each extrusion for twist and then using a wrench-like device to torque the extrusion in the opposite direction.

Pack is the final operation. It involves labeling each extrusion and placing it in a crate for shipping.

Process Flows

Material flows in an extrusion facility are complex. In some ways they resemble the material flows in a job shop environment where scheduling decisions are made and revised on the shop floor in an attempt to accommodate each job's processing needs with the equipment that is not currently being used.

While the author and personnel at the Plant could make some assumptions concerning which manufacturing processes degrade the geometric accuracy of critical angles, data did not exist to validate such assertions. Therefore the project scope included all production processes, creating a need for detailed process flow information. While flow diagrams were available for the Plant, they did not include some types of detailed

information that would have been useful in the study. A portion of the planning phase of the project, therefore, involved analyzing material flows in the Plant. The resulting process flow information was later used in the data survey phase when the rationing of time became an issue. It enabled the author to prioritize manufacturing processes when decisions arose regarding the investment of time in data collection.

Chapter 3: Data Survey

There can be no improvement where there are no standards. The starting point in any improvement is to know exactly where one stands.
Masaaki Imai, Kaizen

The first phase of the study began with data collection. This was necessary to uncover trends which might yield clues concerning quality drivers (to be incorporated into the analytical study phase of the project) and suggestions as to which manufacturing processes should be targeted for further study.

Introduction and Definitions

When an airframe builder orders an aluminum extrusion which has a critical feature angle, two specifications are made: the nominal (target) angle and a tolerance range. A specification of 90° ± 2° means that the engineering design calls for an angle of 90°, but angles ranging from 88° to 92° will be accepted by the purchaser. Tolerance ranges recognize the fact that no two manufactured products are exactly the same, since all manufacturing processes have some variation. Similarly, the variation in a batch of parts may be characterized by calculating the mean and the standard deviation of measurements of the parameter of interest. If the measurements are normally distributed (as many measurements of manufactured goods tend to be), 99.73% of them will fall between the limits of the mean plus and minus three standard deviations [Montgomery, 1991, p. 42]. If the mean of the measurements is equal to the nominal specification, the process is called "centered". Obviously, the goal of having all of the parts fall within the tolerance interval is easier to achieve if the process is centered, since the normal distribution is symmetric

about the mean just as a tolerance level is typically symmetric about the nominal specification. If the process is centered, yet parts still fall outside the tolerance range, it is necessary to reduce the process variance, thereby reducing the standard deviation of the measurements so that they will be clustered more tightly about the mean and, consequently, the nominal specification. Process improvement, therefore, can aim to reduce process variation, center the process, or both. In general, reducing process variation is considered to be more difficult than centering a process.

Characterizing the quality of a batch of extrusions is complex since parameters such as feature angularity vary both along each extrusion and between the extrusions in the batch. One method of characterization is to calculate the standard deviation along each piece in the batch, then average them. The result is referred to in this study as "S_{along}", the sample standard deviation along the extrusions. Then, the mean angle for each piece in the batch is calculated and a standard deviation is obtained from them. This is referred to as "$S_{between}$", the sample standard deviation between extrusions in the batch. Comparing these two parameters gives an indication which type of variation dominates in a given batch. A study of six production lots inspected after stretch (the state of an extrusion after stretch is a good proxy for the state of the final product) showed that S_{along} was greater than $S_{between}$ in all six lots. The mean variance between the pieces was, on average, only 46% as high as the mean variance along the pieces In addition, the mean variance along the pieces was greater than the mean variance between the pieces to a 90% confidence level (see Appendix E: Confidence Interval for Variances Along and Between Extrusions). While this study addressed both S_{along} and $S_{between}$, the analytical study concentrated on S_{along} since the control of $S_{between}$ falls in the category of improving billet-to-billet consistency, an area which is currently under investigation at the Plant.

Instrumentation

The measuring instrument that was chosen for the study was a new digital protractor with the capability of measuring angles to .01 degrees. The angularity study provided opportunities to experiment with different blade configurations and with various attachments to increase the accuracy and reduce the difficulty of taking measurements. A gage capability study of the instrument was performed using two employees who had no previous training or experience with the tool. It resulted in a precision-to-tolerance ratio (P/T) of 0.12. While P/T values of 0.10 or less are generally desired [Montgomery, 1991, p. 393], the reproducibility in the study was high while the repeatability was low, suggesting that the instrument's accuracy would improve significantly when the user(s) became more experienced. Furthermore, the digital protractor was the only commercially available digital angle measuring device. The study proceeded since there were no better alternatives. Blade modifications were made and measurement guidelines were established, however, to improve the accuracy of the inspections. All angle measurements were taken with the same instrument. The author took roughly 80% of the measurements. An assistant accounted for the other 20%.

Job Selection

A conscious effort was made to select a wide range of jobs in order to sample a representative cross-section of the Plant's aerospace extrusion production. The following factors were considered:

- shape (tee, zee, or angle),
- alloy (both 2xxx and 7xxx),
- temper (both O and heat treated tempers),
- thick:thin ratio (asymmetry in wall thickness), and
- aspect ratio (ratio of feature length to wall thickness).

While it was not possible to obtain enough data to conduct a regression study based on these factors, it was hoped that simpler analytical techniques might still identify strong correlations between variations in angularity and the preceding factors.

In all, nine production lots were selected: two zees, four tees, and three angles. All of the lots were extruded on a 6" press and all lots but one were extruded using one-hole dies. There were two reasons for restricting the study to one-hole dies. First, most of the shapes extruded on 6" multi-holed dies have very small cross-sections which make them difficult to measure with the digital protractor. Second, multi-hole dies are affected by additional sources of variation which can affect angularity and are hard to quantify, such as slight dimensional differences between each of the holes in the die. It was felt that these sources of variation could overshadow other sources of variation and add unnecessary complexity. Furthermore, a study of one-hole dies would yield insights which could later be applied to the more complex multi-hole situations.

Inspection Points

As previously mentioned, the finishing area of the Plant is operated as a job shop, with complex material flows and a production schedule that changes constantly as production lots are routed to whichever processing station is currently available. Furthermore, decisions regarding roll and detwist may be made at any point in the production process at which a need for remedial work is identified. As such, even locating a specific lot after it leaves the press area can be difficult.

The ideal situation would have been to inspect the lots immediately after extrusion and then after every subsequent step in the production process. This, unfortunately, was not possible due to production considerations. If a job were extruded a week or more before its scheduled ship date, a hold tag could be used to stop it after a given production process to facilitate an angularity inspection. For some jobs, however, such processing delays were not possible and inspections for angularity were missed, especially if the material was processed and routed on the swing or graveyard shifts.

Most heat treated lots (7xxx series alloys) could not be stopped for inspection between the heat treat and stretch operations because of the necessity to stretch the material quickly after heat treat before age hardening occurs. Thus, while every job was inspected after stretch, none were inspected between heat treat and stretch. A study of heat treat and stretch was conducted later in conjunction with a designed experiment (see "Experiment 4" in Chapter 5) .

Detwist is a manual process which involves 100% inspection. Only the out-of-tolerance parts are processed. Detwist involves applying a twisting moment to the extrusion at a few specific points, not evenly along its entire length. To examine the effect of detwist on feature angularity, care must be taken to measure feature angles at specific locations adjacent to the point at which the twisting moment is to be applied, then to remeasure the same points after processing. Since the sampling techniques and the lot-to-lot statistical comparisons of the general study would not apply well to detwist, it was decided that this operation should be studied separately. Furthermore, the process flow data suggested that less than one third of production lots are routed through detwist. A majority of the pieces that do go through detwist inspection do not require any remedial action. Therefore, the detwist operation affects a relatively small portion of production. No lots were inspected after detwist.

The following table lists the nine lots that were inspected and shows the inspections that were made. In all, over 1,500 angle measurements were taken.

	SHAPE	TEMPER	PRESS	HT	STRETCH	ROLL	AGE/ANN
1	zee	T6511	X	---	X		---
2	zee	T6511	X	---	X		---
3	tee	O	X		X		X
4	tee	T6511	X	---	X		X
5	tee	O	X		X		
6	tee	T76511	X	---	X	X	---
7	Ang	T3511	X	---	X	X	
8	Ang	T76511	X	---	X	X	---
9	Ang	T76511	X	---	X	X	---

X	Inspected
---	Not Inspected
	Not Processed

Sampling

Obtaining accurate angle measurements is very time consuming. Sampling is a technique that can be used to reduce both the number of measurements that must be taken along each extrusion, and the number of extrusions that must be measured in each lot. For most quality indicators (wall thickness, diameter, surface roughness, etc.), experience at the plant has shown that taking two measurements, one at the front and one at the back, of 5-10% of the extrusions in a lot is adequate for characterizing a production run. This is due to the fact that these properties vary in predictable ways along each extrusion and between successive extrusions in a lot, so a considerable amount of information can be obtained from just a few samples. Such predictability has not been demonstrated for angularity, however, so it was not obvious what type of sampling plan would be best.

The point of the study is to analyze the variation of a feature angle along the extrusion. Obviously, at least two measurements would be necessary in order to estimate a variance. While a continuous angularity measurement (100% sampling by, for instance, pulling the entire length of the extrusion through a measurement fixture) may be optimal from an accuracy standpoint, the necessary instrumentation was not available. Conversely, taking only two measurements on each extrusion would be most desirable operationally, but might also degrade accuracy to an unacceptable level.

The key to minimizing the amount of effort spent on data collection (thereby maximizing the number of jobs that can be inspected) is understanding the relationship between accuracy and the number of samples that are measured. To get a feel for the effect of sampling on variation characterization, two or three extrusions were selected at random from several production lots. For each extrusion, a reference angle was measured at three locations, front, center, and back, then the same angle was measured at approximately 18" intervals, which are referred to here as "profile" measurements. The standard deviation of the reference angle was estimated from the range of the three-point measurements, and was calculated from the profile measurements (with a sample size of three, an estimate of the standard deviation using a range will deviate from the calculated standard deviation by less than 1% [Montgomery, 1991, p.204]). A scatter plot of these data points is shown below in Figure 5.

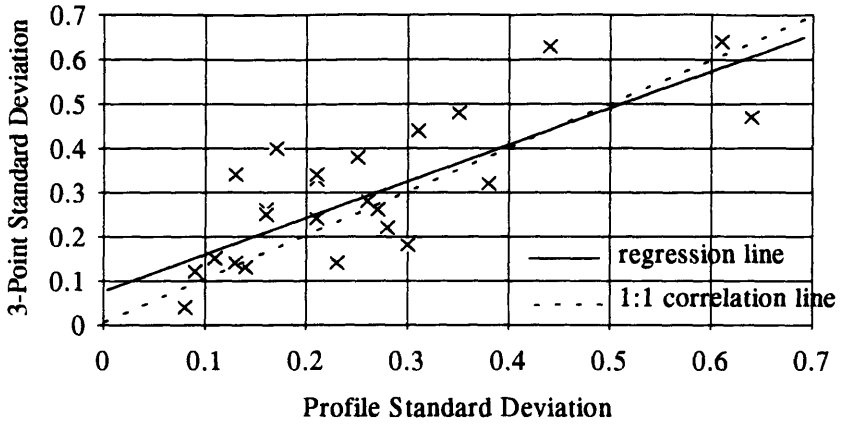


Figure 5. 3-Point Measurements vs. Profile Measurements

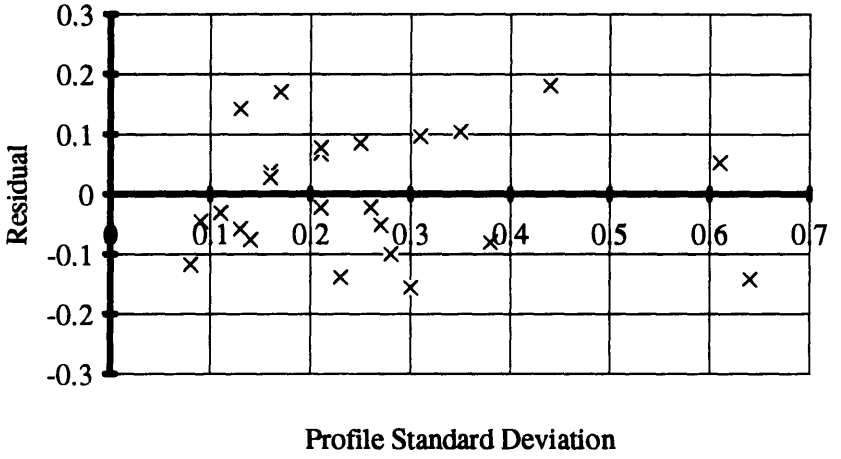


Figure 6. Residual Plot of 3-Point Measurements vs. Profile Measurements

If the three-point estimates were identical to the profile estimates (which are assumed here to be "true" measures of the reference angle's variation), the data points in Figure 5 would lie along the dashed, 1:1 correlation line. They do not, which indicates that sampling error exists in the three-point estimates. A least squares regression line

through the data, however, lies roughly on the 1:1 correlation line. A residual plot (Figure 6, above) confirms that the three-point measurements are relatively unbiased by showing that the error of the regression model is randomly distributed about a mean of zero with no discernible trend or pattern. Since the three-point measurements are unbiased, an average of the three-point standard deviation estimates for an entire lot should be very close to the "true" standard deviation for the lot, since the sampling errors will tend to average one another out.

Similar analysis was performed on means calculated from the three-point and profile measurements. Again, the three-point measurements seem adequate for characterizing a production lot, especially when data for many individual pieces are averaged together to reduce the effect of sampling errors.

Armed with this knowledge, front, center, and back angle measurements were taken on 100% of the pieces comprising each production lot under 40 pieces and on 50% of the pieces in orders over 40 pieces (Inspection procedures and sample data sheets can be found in Appendixes B, C, and D). Though this sampling plan appears to be adequate for the general characterization of production lots (where data from many pieces are averaged together to produce a single value for the lot), it was significantly altered for inspecting pieces produced in the designed experiments since they require much greater accuracy (see Chapter 5).

Production Processes

Inspections were performed at various points in the production process in order to gain an understanding of how variation in angularity changes as the material is transformed from billet to finished product. Figure 7, below, summarizes the results of this portion of the survey. The chart traces the variance of the feature angle for each lot that was

included in the study. The markers on the chart show the variance of the feature angle *after* the lot is processed by the designated operation (for example, the two markers for age/anneal show the post-age/anneal variances for the two tee lots that were inspected after processing by the age/anneal oven). Operations that were not performed or were not inspected are not designated by markers. The heat treat operation, for instance, would lie between press and stretch on the chart. Only the two tee lots that are labeled "non-HT" were not heat treated. No markers are shown for the lots that were heat treated because they were not inspected between heat treat and stretch.

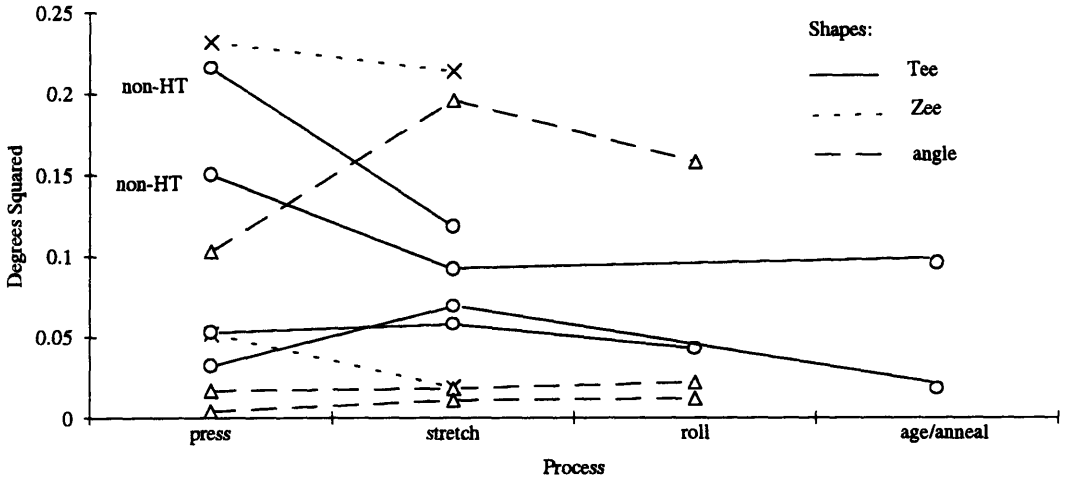


Figure 7. Variance by Process

Several interesting points are illustrated by the process variance chart. First, the roll and age/anneal operations have very little effect on variation of angularity. Roll shows a neutral-to-slightly positive effect and age/anneal shows one positive effect and one slightly negative effect.

Second, variation changes most dramatically between the press and stretching operations. This is to be expected since both the heat treat and stretch operations involve large stresses (thermal during quenching and tensile during stretching) which have the potential to distort feature angles. The two non-heat treated lots show the effect of stretch alone. Stretching reduces variation in both cases with the higher variation lot experiencing the greater absolute reduction. It is interesting, however, that the variation of each lot decreased by approximately 50%. The results for the other seven heat treated lots are mixed, with four lots experiencing increases in variation, two decreases, and one no change in variation. If one assumes that stretching can only reduce variation (an assumption that is reasonable physically and is supported by the data presented here), then the press-to-stretch data for the heat treated lots would imply that heat treat increases variation (another logical assumption), while stretch works to reduce it. Thus, the variation present after stretch (which approximates the eventual variation of the lot at shipping) depends on three things: the effect of stretch, the effect of heat treat, and the initial variation created by the extrusion process. The fact that most of the lots experienced only small changes in variation between the press and stretch implies that the effects of heat treat and stretch are roughly equal and opposite, and so tend to cancel one another out. Furthermore, the press-to-stretch change in variation seems to scale with the gross magnitude of the variation at the press. The lots that were extruded with very little variation in angularity experienced small press-to-stretch changes in variation (in either direction) and the lots that were extruded with high degrees of variation experienced bigger shifts.

Taken as a whole, these observations indicate that *controlling variation at the press is the key to producing a finished product with minimal variation in angularity.* The stratification of the data in the chart further supports this view. With one exception, the variation of the lots fluctuate within narrow, non-intersecting bands as they pass through the various finishing operations. Lots that leave the press with low variances are

shipped with low variances. Lots that leave the press with high variances have high variances at shipping. Thus, *an improvement in the ability to control angularity during extrusion would provide the most leverage for reducing variation in the final product.*

Variation at the Press

In direct extrusion, most geometric quality parameters (wall thickness, diameter, etc.) vary in fairly predictable ways from the front to the back of each extrusion. To check for similar trends in angularity, the profile data was analyzed for signs of changes in the level of variation along the extrusions and for general front-to-back trends in the raw data.

Figure 8, below, shows a scatter plot containing standard deviation estimates for the front halves of each billet plotted against the corresponding standard deviation estimates for the back half of the billet. The data seem to be randomly distributed about the 1:1 line. Thus it appears there is no significant difference in variation between the front and back halves of the extrusions. Likewise, as shown in Figure 9, a similar analysis of standard deviation estimates for the front 2/3 and the back 1/3 of each piece yields the same conclusion. Confidence intervals for the data shown in Figs. 8 and 9 confirm that no statistically significant difference exists between the variation data from the fronts and backs of the extrusions.

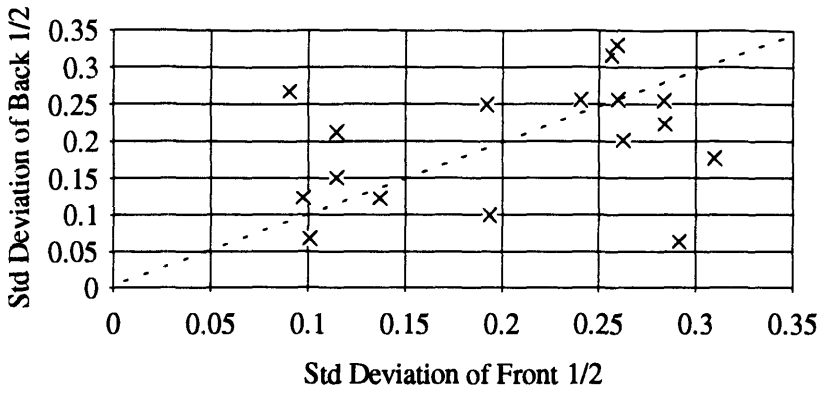


Figure 8. Front Variation vs. Back Variation

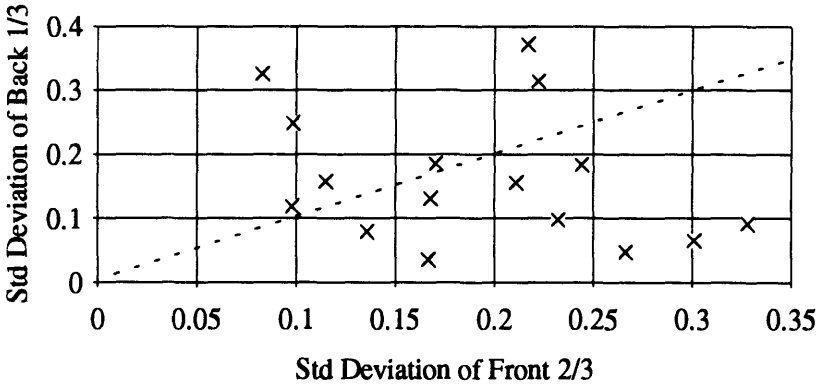


Figure 9. Front Variation vs. Back Variation

Figures 1 through 4 of Appendix A contain plots of the angle measurements at each point along the extrusions. The pieces are grouped by length with only three to five extrusions plotted on each chart for clarity. While Figure 1 seems to imply that the feature angle drifts away from nominal along the extrusion, the other plots do not. No obvious patterns exist. Some pieces miss the nominal specification by a degree or more. No trends are apparent.

Overall, the profile data show no front-to-back trending in either variability or raw angle measurements.

Geometric Factors at the Press

As previously mentioned, the time consuming nature of data collection made it impossible to obtain enough information to conduct a meaningful regression study which could identify geometric factors as drivers of variation in angularity. As such, less formal data analysis techniques, primarily charting, must be relied upon to gain insight into these relationships. While charting variation versus a single geometric parameter ignores the potential effects of all other geometric factors as well as differences in running conditions (speeds, temperatures, etc.), it was hoped that it might reveal any strong relationships which exist.

Figure 10, below, is a plot of the standard deviation of the feature angle at the press vs. aspect ratio (length/thickness). The aspect ratio of both legs which define the feature angle were calculated and the larger one was used for the plot. The dashed line is a linear regression line that was fit to the data and forced to pass through the origin. This graph shows that, in general, variation is higher for angles between long, thin legs than for angles between short, stubby legs. This confirms intuition and agrees with the production experience at the Plant which has shown that the higher a feature's aspect ratio, the more difficult it will be to produce it without distortion.

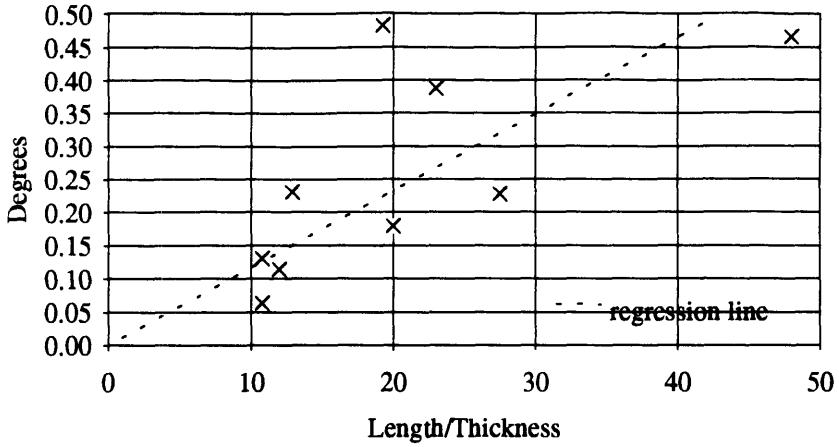


Figure 10. Standard Deviation at Press vs. Aspect Ratio

Figure 11, below, is a plot of the standard deviation of the feature angle at the press vs. extrusion circle. The extrusion circle is a rough measure of the size of the cross-section of the part being extruded. It is the diameter of the smallest circle that can fully contain the cross-section of the extrusion. Since this survey primarily deals with shapes that were extruded on one-hole dies, extrusion circles also correlate with the proximity of the extremities of the die opening to the perimeter of the die. For instance, a shape with a large circle size extends closer to the perimeter of the die than a shape with a small circle size. Figure 11, therefore, implies that, other things being equal, a die opening that is close to the perimeter of a die will experience more variation in feature angularity than one that is closer to the center of the die.

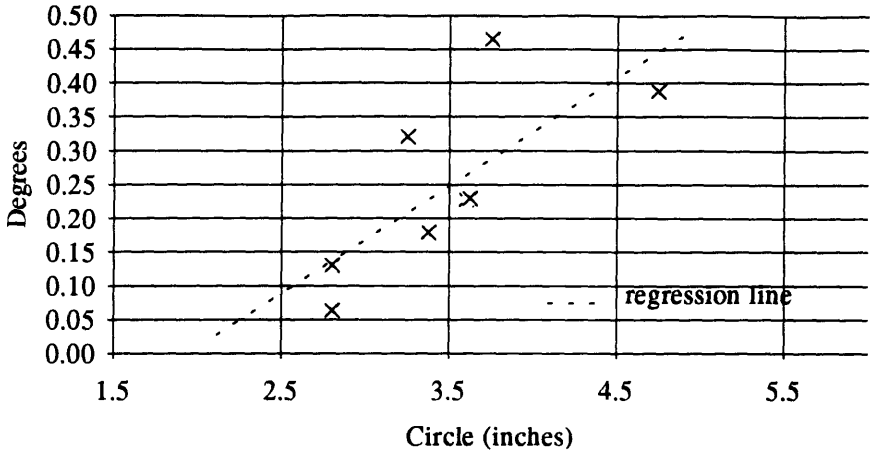


Figure 11. Standard Deviation vs. Extrusion Circle

Figure 12 is a plot of the standard deviation of the feature angle at the press vs. the extrusion ratio (area of the billet/cross-sectional area of the part). Except for one outlier, the points possess a high degree of linearity. A linear regression line (calculated without the outlier) is shown on the graph. At first glance, the downward sloping trend is somewhat surprising. It makes sense, however, if one takes into account the fact that all of these production lots were extruded on the 6" press and that the wall thicknesses were similar for all of the jobs. In that case, differences between extrusion ratios are caused primarily by differences in the lengths of the legs defining feature angles. Therefore, high extrusion ratio parts have, in general, short legs and low extrusion ratio parts have long legs. The differences in leg length naturally translate into differences in circle size. Figure 12 verifies this by demonstrating the relationship between circle size and extrusion ratio. Incidentally, the outlier in Figure 12 is the same data point that is an outlier in Figure 11.

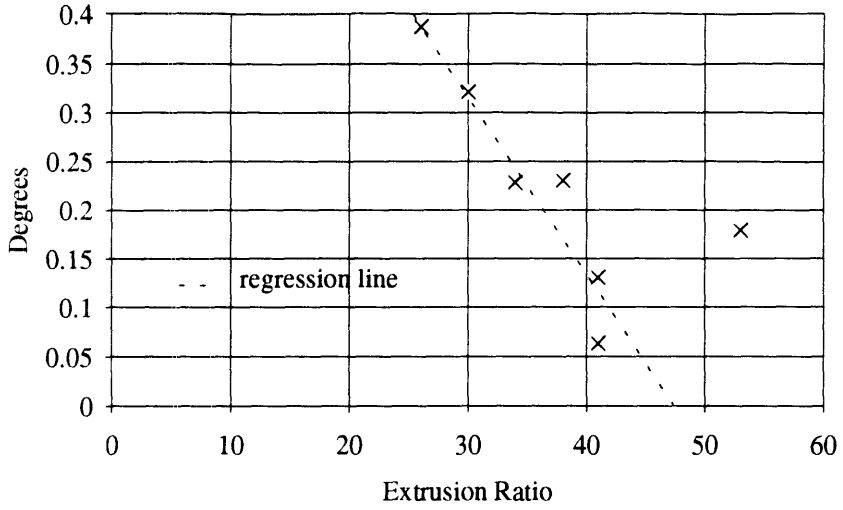


Figure 12. Standard Deviation at Press vs. Extrusion Ratio

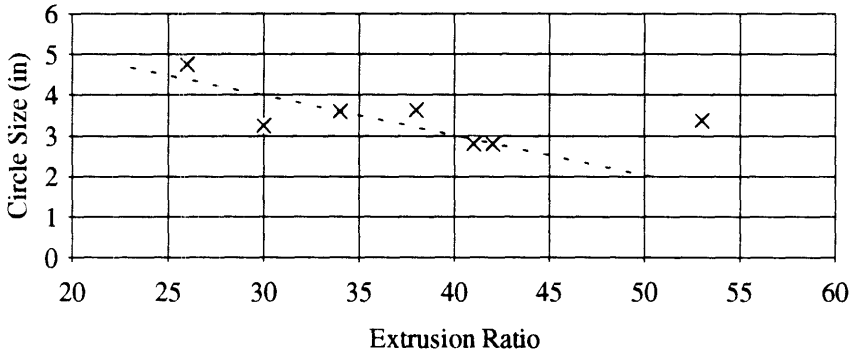


Figure 13 Extrusion Circle vs. Extrusion Ratio

Figures 10 through 12 strongly suggest that the variation of a feature angle at the press is highly influenced by the proximity of the die opening to the perimeter of the die. Shapes which are concentrated at the center of the die suffer less variation than shapes which are placed close to or extend to the perimeter of the die. This result suggests that

material flow patterns within the unextruded portion of the billet during extrusion greatly influence variation in angularity.

The survey data was also analyzed with respect to basic shape type (tee, zee, or angle), die factor (perimeter of the cross-section/cross-sectional area), and the ratio of the thicknesses of adjacent legs defining the feature angle. While these factors seemed to be insignificant with respect to variation in angularity, a larger dataset may have improved the resolution of the analysis enough to reveal subtle relationships.

System Capability

Estimating the ability of the production system to produce finished extrusions to nominal specifications for angularity is an important part of the data survey. Statistical process control typically defines the capability of a process with the Cpk parameter calculated for a group of parts produced by the process in question. Cpk is defined as follows:

$$Cpk = \min\left(\frac{USL - \mu}{3\sigma}, \frac{\mu - LSL}{3\sigma}\right)$$

where μ is the mean and σ is the standard deviation of the data describing the quality parameter that is of interest and USL and LSL are the upper and lower specification limits (endpoints of the tolerance interval) for the same parameter. A process is considered "capable" if Cpk is greater than or equal to 1.25 (or 1.33 according to some sources). The numerator of the ratios inside the brackets give an indication of where the mean of the data lies in relation to the specification limits. If the mean is on target (equal to the

nominal specification), then USL-μ and μ-LSL will be equal and Cpk reduces to Cp, which is defined as :

$$Cp = \left(\frac{USL - LSL}{6\sigma} \right)$$

If the process is not centered (the mean is not equal to the nominal specification), Cpk penalizes the process for being off target. Therefore, process capability has two parts: the spread of the data taken from the process (represented by the standard deviation in the denominator), and the amount the mean is "off target" (represented by the numerator). Cpk was used exclusively for this study since both variation and the mean of feature angles are important to the Plant's customers.

Data from the stretch operation was used as a proxy for data from the finished products as it has been demonstrated that angularity changes very little after stretch. Six of the nine lots that were inspected had +/- 2° tolerances for angularity and three had +/- 1.5° tolerances based on the aspect ratios of the legs which defined the feature angles (per the Aluminum Association guidelines). The following table shows the capability of the production system as inferred by the post-stretch inspection of the nine production lots. Cpk values are also calculated for varying tolerance intervals to explore the system's ability to cope with the special tolerances that customers are now demanding with increasing frequency.

Cpk Estimates

		+/- 2.0	+/- 1.5	+/- 1.0	+/-.50
1	zee 1	1.16	0.80	0.44	0.08
2	zee 2	3.50	2.30	1.10	0.00
3	angle 1	1.09	0.72	0.34	0.00
4	angle 2	4.77	3.53	2.30	1.06
5	angle 3	5.57	3.99	2.42	0.85
6	tee 1	2.19	1.64	1.09	0.54
7	tee 2	2.01	1.38	0.74	0.11
8	tee 3	1.61	1.12	0.64	0.16
9	tee 4	2.46	1.76	1.07	0.37

* The customer-specified tolerance limits for each production lot are indicated by shading

The previous table shows that with ± 2.0 degrees tolerance limits, seven of the nine lots are acceptable by the Cpk ≥ 1.25 rule. The shaded values show that seven of the nine lots were in tolerance by the same criterion using the actual tolerance limits for the individual lots. *This result verifies the Plant's ability to hold the Aluminum Association's current tolerances for angularity. In addition, it should be noted that the Plant has been able to hold tighter tolerances (usually half-industry standard tolerances) on angularity on individual special orders in the past.* This was achieved through greater inspection and rework. Unfortunately, such measures are too expensive to use on a routine basis in an environment where most customers demand tight control of angularity. Adjusting the manufacturing process to achieve better control over angularity seems to be the only economically feasible solution.

As one tightens the tolerance limits, six, two, and then zero lots would be in tolerance at +/- 1.5, 1.0, and .5 degrees respectively. *Again, it should be noted that these lots did not receive extra inspection and rework to reduce variation in angularity since the orders specified standard industry tolerances.*

While reducing variation without affecting the mean would be sufficient to keep most lots in tolerance at +/- 1.0 to 1.5 degrees, achieving +/- .5 degrees requires tight control of both variation and the mean angle. A two-step process for bringing feature angles into control could work very well in this case since die repair techniques are already routinely used to adjust the mean angle if a part is considered out of tolerance for angularity. These techniques, however, do not seem to have an effect on variation in angularity. If process levers for reducing variation could be discovered, both sets of tools could be used simultaneously to narrowly focus feature angularity on the nominal specification, thereby meeting even the most stringent customer specifications for angularity.

Results

The data survey of feature angularity has determined that the current production system is capable of producing parts to current tolerances for feature angularity. The increasing frequency of special tolerance orders, however, is a reminder that today's acceptable quality levels may not be acceptable tomorrow. Fortunately, the survey has yielded information which can be used to direct the investigation in the analytical study phase of the project. Chiefly, it has shown that controlling angularity at the press will provide the most leverage over the finished product; therefore, the analytical study should concentrate on the extrusion process. A secondary target for improvement would be the heat treat operation, which has a negative impact on angularity and counteracts the beneficial effects of the stretch operation. The strongest geometric factor affecting variation in angularity was found to be the proximity of the die opening to the perimeter of the die. This fact suggests that the analytical study should develop a better understanding

of the link between material flow in the billet during extrusion and variation in angularity. When such a link is found, real process improvement will be possible. Finally, the study has demonstrated that the problem of variation in feature angularity is very complex. Experimentation will be required to verify and quantify the results of any ideas for improvement that arise from the analytical work.

Chapter 4: Analytical Study

"Mental Models" are deeply ingrained assumptions, generalizations, or even pictures or images that influence how we understand the world and how we take action.

Peter M. Senge, The Fifth Discipline

Introduction

In simplest terms, direct extrusion involves pushing material through a hole machined in a disc-shaped metal die. If the hole in the die does not change over time (due to erosion, aluminum build-up on the bearing surface, distortion from heat and pressure, etc.), it stands to reason that the extrudate will have a constant cross-section geometry along its length and that each successive extrudate will be an exact replica of the ones preceding it. A production run of several billets would then involve a series of repeatable, steady-state processing steps. Geometric variation should be a non-issue. Unfortunately, the real world is not so tidy. This highly simplified description of the extrusion process neglects physical phenomena which conspire to add variation to the process.

In reality, almost no portion of the extrusion cycle is accurately characterized by steady-state conditions. In addition, successive billets will experience varying processing parameters which greatly influence repeatability. The net result is the existence of geometric and metallurgical nonuniformities both along individual extrusions and between successive extrusions in a production run. To control these variations in the product, one must first understand the underlying physics of the process well enough to identify the factors which lead to nonuniformities in the product. Then one must link these factors with the processing parameters which influence them. The resulting cause and effect relationships will provide the practitioner with the knowledge he needs to improve the process.

Extrusion Physics

The extrusion press compresses a billet to the point at which it begins to shear. The billet material, following the path of least resistance, flows through the die opening. The orientation of stresses within a billet placed in compression is determined by the mechanical properties and geometry of the billet and the geometry of the tooling. Stresses within the billet cause local plastic deformation. The resulting material flow patterns within the billet determine flow patterns within the die, and flow patterns within the die determine the final geometry of the extrudate. Therefore, conditions within the billet are of utmost importance for the control of the geometry of the extrudate.

Flow Patterns Within the Billet

Numerous studies have been performed to analyze material flows within billets during extrusion. In most cases, a billet is sawn in half lengthwise and inscribed with a uniform grid on the mating surfaces. The pieces are rejoined and inserted into an extrusion press. The extrusion process is initiated then stopped at the point in the cycle which is of interest. The billet halves are removed from the press and examined. Flow patterns in the material can be observed by examining the distortion of the squares of the grid that was machined onto the mating surfaces. In this way, the level of distortion (shear) and direction of material flow can be readily identified over the cross-section of the billet. These studies reveal the existence of several distinct flow regimes during direct extrusion [Tashiro, 1992, p. 203].

Three distinct flow regions form early in the extrusion cycle. Figure 14 illustrates metal flows in an aluminum billet extruded through a flat-faced, round, one hole die.

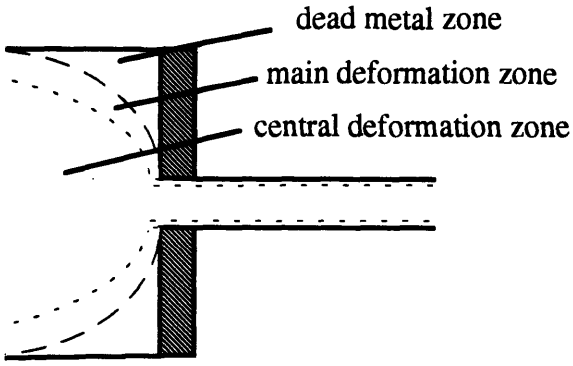


Figure 14. Flow Regimes During Direct Extrusion

At the center of the billet, material is left unsupported due to the presence of the die opening and, so, the material here is the first to begin flowing. This region also endures less shearing due to the material's distance from the container wall and the fact that it can flow into the die opening without a significant change in flow direction. This region is called the central deformation zone and is roughly conical in shape, especially near the front of the billet. Material from the central deformation zone will form the core of the extrudate.

Surrounding the central deformation zone is another conical region called the main deformation zone. As the name implies, this is the region in which material is most intensely sheared. This intense shearing is caused primarily by the redirection of metal flow at the front of the billet as the flowlines converge on the die opening and, to a lesser degree, by friction between the billet and the container wall. Material in the main deformation zone flows closest to the die bearing to form the surface layer of the extrudate. Figure 14 shows the main deformation zone collapsing in, toward the die opening at the front of the billet.

The billet material outside of the central deformation zone, adjacent to the container wall near the die opening, does not flow and so endures very little shearing.

This region is called the dead metal zone (DMZ). Material flowing along the interface between the dead metal zone and the main deformation zone will form the surface of the extrudate. *The shape of the dead metal zone determines the path through which metal enters the die opening.*

Factors Affecting the Shape of the Dead Metal Zone

The shape of the dead metal zone is a function of many factors. Obviously, the shape of the die opening and its layout on the die will influence the geometry of the dead metal zone. Generally, the dead metal zone will slope upward from the perimeter of the die opening to the container wall. For openings that lie at the die's periphery, however, the close proximity of the container wall changes the shape of the dead metal zone on one side, causing asymmetry. The slope of the dead metal zone will be higher at points on the die opening perimeter which are close to the container wall than at points which are closer to the center of the die (see Figure 15). Thus the dead metal zone is more symmetric for centered parts with small circle sizes than for non-centered parts or parts with large circle sizes. This fact seems significant when one recalls Figure 11 from the data survey, which indicates that a plot of variation in angularity vs. circle size shows a positive correlation.

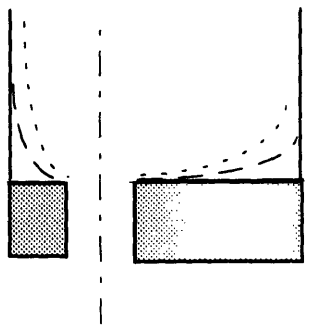


Figure 15. The Effect of Die Layout on the DMZ

The shape of the dead metal zone is also affected by instability and the level of shearing inside the billet during the extrusion cycle. At the beginning of the press stroke, when only a small portion of the billet has been deformed, the DMZ is very large and has a high slope (see Figure 16, below).

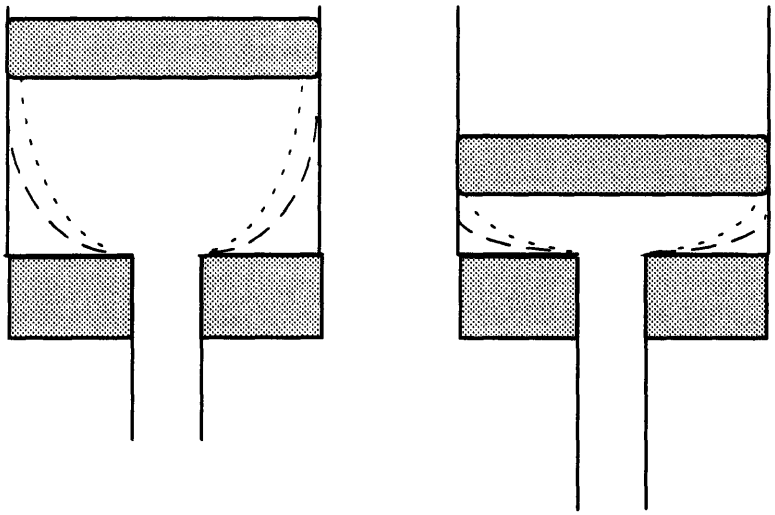


Figure 16. The Effect of Billet Length on the Slope of the DMZ

As more material is sheared, the DMZ shrinks in size and its slope decreases. Late in the cycle, the DMZ can become very small and metal flow in the main deformation zone may reverse direction, flowing toward the back of the billet to fill the void that develops between the billet and the dummy block at the center of the container. This can also affect average flow velocities across the die opening if the flow reversal is nonsymmetric about the centerline of the die opening. The intensity of this instability at the end of the extrusion cycle is influenced by the length of the billet which is not extruded, but removed from the press as "butt". A billet extruded to a very short butt length may encounter intense instability as the billet material struggles to fill the void at the back of the billet and to align its velocity with the runout direction.

Studies [Tashiro, 1992, p. 203] have shown that the shapes of the three deformation zones are significantly influenced by the temperatures of the billet and the die. Though the literature reviewed by this author does not provide an explanation for these phenomena, it would appear reasonable that the softening of aluminum which occurs at higher temperatures causes a change in the size and slope of the DMZ. It also seems logical that the difference between the billet and die temperatures is significant, since heat transfer between the die and the billet can cause localized temperature changes at the front of the billet. The resulting changes in local flow stresses may also change the shape of the flow regions adjacent to the die opening.

The same studies have shown that the geometry of the die entrance can have a drastic effect on the shape of the three flow regions. For example, switching from a flat faced die to a conical die (see Figure 17) radically altered the shape of the dead metal zone. *These findings suggest that modifications in die opening geometry may be useful for controlling the shape of the flow regimes in the area immediately adjacent to the die opening.*

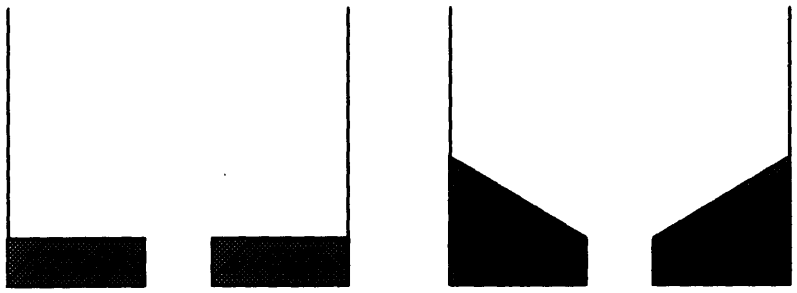


Figure 17. Flat vs. Conical Die

Distortion Mechanisms

Imperfections in feature angularity (when the feature angle of the final product is not the same as the feature angle machined into the die) occur when distortions affect the locations of the features themselves. To explore the causes of these geometric distortions, it is useful to think back to the simplified description of the way an extrusion is formed from the introduction to this chapter and ask the question What can go wrong? From a final geometry standpoint, there are two things which can go wrong when metal flows into the die. Metal may flow at velocities which are not uniform across the die opening, and metal may flow into the die opening in a direction which is not parallel to the stroke of the press and the intended runout direction. These, then, are the generic causes of distortion in feature location. *Variations in the factors which cause such distortions cause the level of distortion to fluctuate and, hence, variation in feature angularity.*

Nonuniform Flow Velocities

The velocity of metal flowing through a die opening (or a portion of the die opening) is influenced by several factors. Ram speed obviously affects the velocity of the metal, as do the length of the bearings (through the effects of friction) and the geometry of the die opening (geometry of the entrance, cross-sectional area of the opening, etc.). When one portion of a die opening experiences a higher flow rate than the rest of the opening, the width and thickness of the fast-flowing feature will be increased slightly by what is commonly called "better fill". Such a feature will also exhibit an increase in length. The runout length of the feature will, however, be constrained by adjacent features with shorter runout lengths. This can cause the extrudate to "hook" away from the intended runout direction and will result in longitudinal stresses in the extrudate. The fast running feature will, in general, be placed in compression and the slower running features will be in

a state of tension as different portions of the extrudate's cross-section attempt to achieve their "natural" lengths. Thin, high aspect ratio features placed in compression may buckle as a means of relieving internal stresses. This causes the "waviness" which is commonly seen in the stems of large, thin-walled tee shapes. Waves in a feature along the length of an extrudate will, of course, cause variation in the angle measured between said feature and adjacent features. While this phenomenon is potentially important from a feature angularity standpoint, it is, in practice, of less concern than other distortion mechanisms, since proper die design can virtually eliminate unequal flow velocities across die openings. Even after a die is manufactured, die repair techniques can alleviate waviness in all but the most severe cases. Slight differences in flow velocities, however, may go unnoticed or uncorrected.

This distortion mechanism is easy to identify by checking the extrudate for flatness along its length. It is also relatively easy to correct. As such, this study will concentrate on the more perplexing distortion mechanism: nonparallel flow directions.

Nonparallel Flow Directions

The metal flows exhibited in Figure 14 show the redirection that occurs as metal approaches the die opening. At the front of the billet, metal from the main deformation zone and from the periphery of the central deformation zone must bend in, toward the axis of the billet, to enter the die. The shapes of the dead metal zone and of the two deformation regions in this area will determine the direction from which metal from the peripheral regions enters the die. In a case where the DMZ exhibits radial symmetry about the intended runout direction, the *mean direction of flow* into the die opening will be parallel to the intended runout direction since symmetry will cause localized nonparallel flows from the peripheral regions to balance one another. Geometric distortion due to nonparallel flow directions will not occur in this case. *Asymmetry in the DMZ, however,*

will cause the mean direction of flow into the die opening to deviate from the intended runout direction. The resulting nonparallel mean flow direction has the potential to cause geometric distortion in the final product.

The velocity profile at the plane of the die opening is complex, as the attempt to simplify it by defining a mean flow direction would suggest. The state of stress across the plane of the die opening is even more difficult to describe. The analysis of this situation may be greatly simplified if one assumes that the mean direction of flow concept can be substituted for the complex velocity profile, and that the complex set of forces which act on the plane of the die opening can be summed vectorally into a resultant force which is parallel to the mean direction of flow. While it is not clear that these simplifying assumptions are valid, one's confidence in them would grow if the results of the ensuing analysis were to agree with the conclusions of the data survey and if the predictions which result from the analysis could be proven by the experimental phase of the project.

A benefit of first performing a simplified analysis is that it is often sufficient for capturing the important elements of a problem. This can enable the process improvement practitioner to invest more time experimenting with process improvement and less time constructing an exhaustive analytical model. Furthermore, a simplified but reasonably accurate analysis may actually provide a better basis for building an effective "mental model", since complexity in a model tends to obscure important relationships and reduce usefulness.

Figure 18, below, illustrates the simplifying assumptions outlined above in a case in which asymmetry in the DMZ has caused a nonparallel flow direction. Furthermore, the resultant force has been decomposed into its longitudinal and lateral portions, or, its $\parallel$ and $\perp$ components (for parallel and perpendicular to the runout direction).

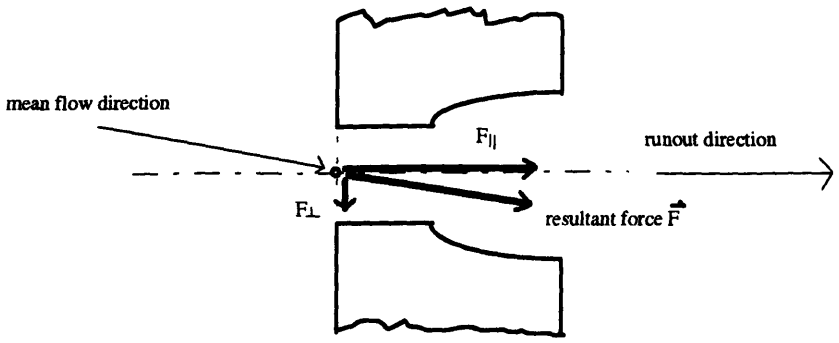


Figure 18. Nonparallel Flow Direction

The key to the role of asymmetric flow directions in geometric distortion would seem to be F⊥, the lateral component of the resultant force. Though the inertial effect of F⊥ is small (forces found at the die opening are large, but they are accompanied by relatively low flow velocities), the frictional effects may be quite large. These effects may be investigated with the help of a free body diagram. Figure 19 shows billet material that is sandwiched between two die bearings. We will neglect end effects by performing a 2-D analysis of a slice of material taken from the middle of a long die opening of constant thickness (t) and constant bearing length (L). Such an element might be found, for instance, in the center of the stem of a tee-shaped die opening. This analysis also assumes the extrudate moves along the runout table without any drag so that no force exists at the die exit to resist runout. The element is affected by the two components of the resultant force previously mentioned (F||, and F⊥), two friction forces (Fr1 and Fr2, referring to the friction forces at bearing surfaces 1, and 2 respectively), and two distributed forces along the bearing surfaces, f1 and f_2. f1 and f_2 are assumed to be uniformly distributed (for simplicity), and represent the force that the die bearings place on the billet material in order to deform it into the final geometry of the extrudate.

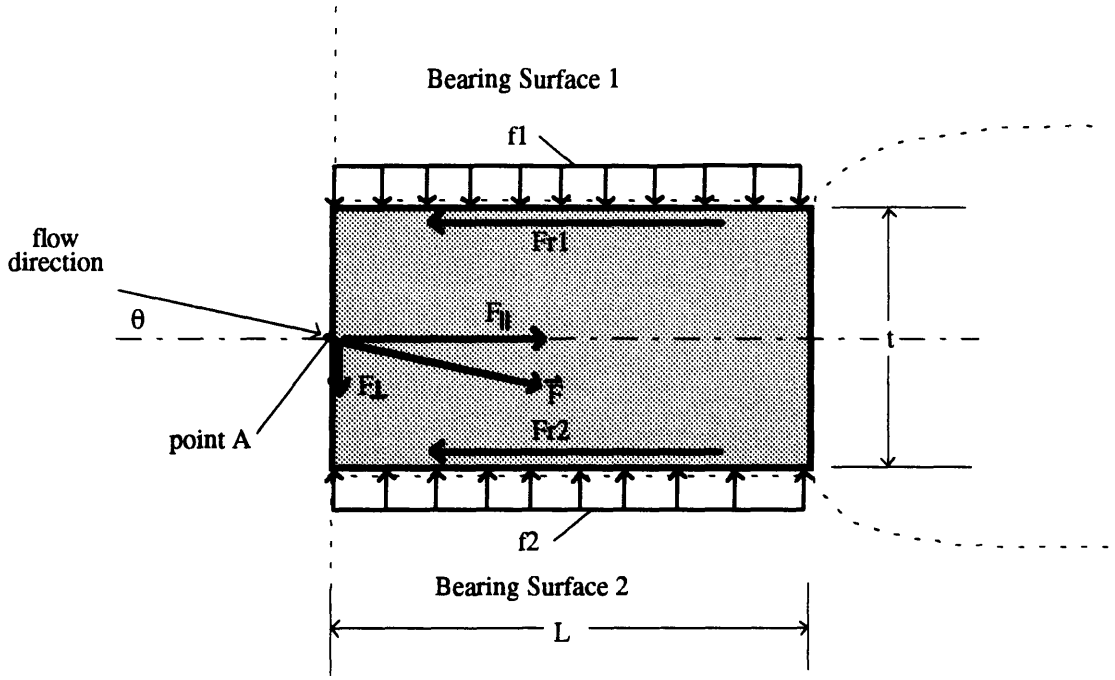


Figure 19. Free Body Diagram

The exact values of the forces shown in Figure 19 would be very difficult to obtain through measurement or calculation. Simple geometry, however, *may* be sufficient to yield insight into the relationship between friction at the bearing surfaces and asymmetric flow directions.

Starting with a few identities:

1) $F\perp = \vec{F}\sin\Theta$

2) $F\| = \vec{F}\cos\Theta$

Sum moments around point A:

3) $$\sum M_A = Fr_1\left(\frac{t}{2}\right) - Fr_2\left(\frac{t}{2}\right) + f_2 L\left(\frac{L}{2}\right) - f_1 L\left(\frac{L}{2}\right) = 0$$

Sum forces:

4) $$\sum F_{II} = \bar{F}\cos\Theta - Fr_1 - Fr_2 = 0$$

5) $$\sum F_{\perp} = \bar{F}\sin\Theta + f_1 L - f_2 L = 0$$

Combine equations 3) and 5):

6) $$Fr_1\left(\frac{t}{2}\right) - Fr_2\left(\frac{t}{2}\right) + \left(\frac{L}{2}\right)\bar{F}\sin\Theta = 0$$

Rearrange equation 4:

7) $$\bar{F} = \frac{Fr_2 + Fr_1}{\cos\Theta}$$

Combine 6) and 7):

$$\mathrm{Fr}_1\left(\frac{t}{2}\right) - Fr_2\left(\frac{t}{2}\right) + \left(\frac{L}{2}\right)\left(\frac{\sin\Theta}{\cos\Theta}\right)(Fr_2 + Fr_1) = 0$$

$$Fr_1\left[\left(\frac{L}{2}\right)\tan\Theta + \frac{t}{2}\right] + Fr_2\left[\left(\frac{L}{2}\right)\tan\Theta - \frac{t}{2}\right] = 0$$

8) $$Fr_2 = \left\{ \frac{\frac{t}{2} + \left(\frac{L}{2}\right)\tan\Theta}{\frac{t}{2} - \left(\frac{L}{2}\right)\tan\Theta} \right\} Fr_1$$

or, $Fr_2 = \{K\}Fr_1$ where $K = \dfrac{\frac{t}{2} + \left(\frac{L}{2}\right)\tan\Theta}{\frac{t}{2} - \left(\frac{L}{2}\right)\tan\Theta}$, the coefficient of frictional asymmetry

Figure 20 shows K calculated for various values of Θ. In this example, L is assumed to be .2 inches. Values for K are give for t values of .115 and .080 inches.

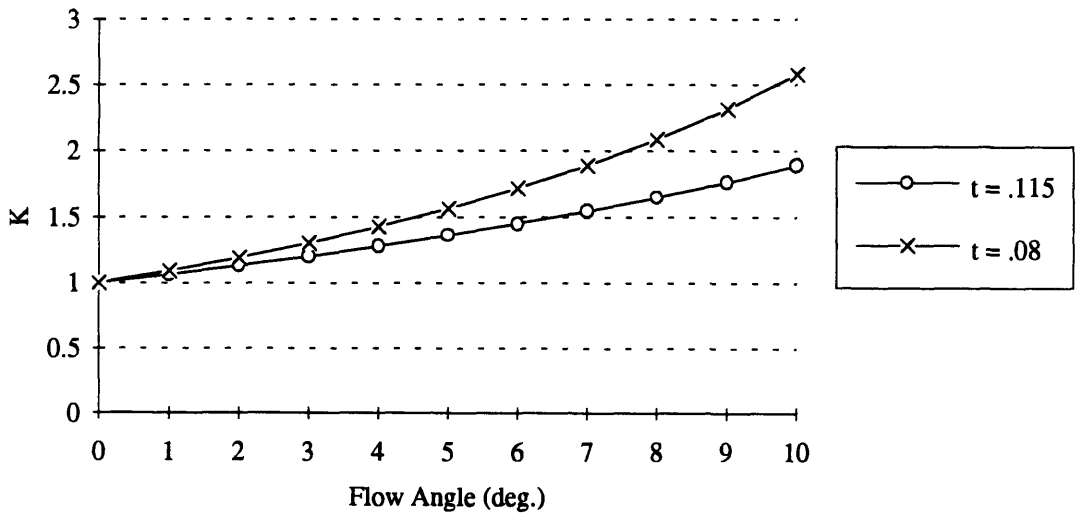


Figure 20. Coefficient of Frictional Asymmetry (K) vs. Flow Angle

So far the analysis has established that material flowing symmetrically into the die opening will encounter equal friction forces at the two parallel bearing surfaces (assuming equal bearing lengths). In this case, runout will be parallel to the press stroke and no distortion will occur. If, however, material is flowing into the die opening at an angle to the intended runout direction (like Figure 19) the friction force at the impinged bearing surface (bearing surface 2 in the diagram) will be greater than the friction force at the opposing bearing surface (bearing surface 1 in the diagram) by a factor which is determined by the coefficient of frictional asymmetry, denoted by K. Material flow at the high-friction bearing surface will be limited by the increase in drag and a nonsymmetric velocity profile will develop across the die opening from bearing surface 1 to bearing surface 2 (see Figure 21, below). This velocity profile will cause the extrudate to "hook" away from the intended runout orientation in the direction of the angle of flow direction asymmetry. This effect explains the relationship between runout direction and flow direction asymmetry that has been observed by researchers [Tashiro, 1992. p. 196].

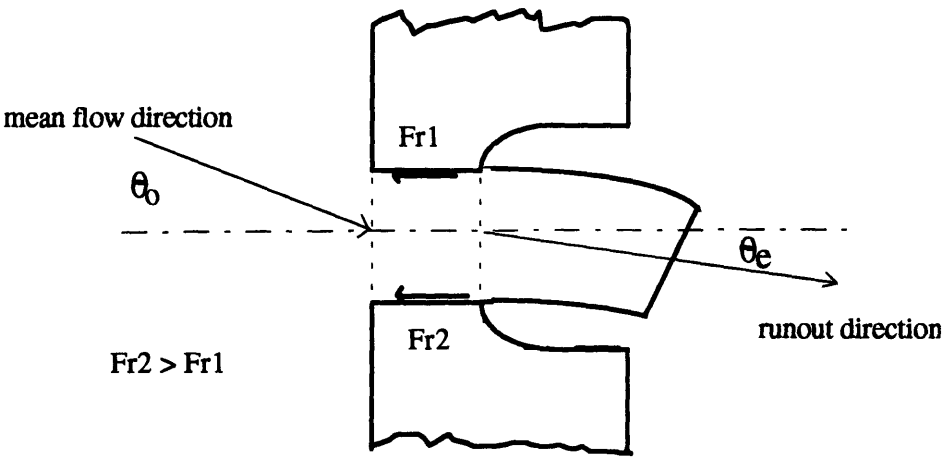


Figure 21. The Effect of Frictional Asymmetry on Runout Direction

This frictional effect readily translates into variations in feature angles. For instance, if one leg of a simple L-shaped angle exits the die parallel to the runout direction but the other leg attempts to exit in a slightly different direction, the angle between the two legs will differ from the angle between the legs in the die opening. If the flow direction asymmetries vary throughout the extrusion cycle or vary from billet to billet, the result will be a feature angle which varies along the extrudate or between successive billets, respectively. While the mental model that has been developed thus far considers this to be the primary driver of variation in feature angularity, it should be noted that other factors which are not included in this two-dimensional model may also play a role in some cases. The main goal of the experimentation phase of the project will be to test this mental model. At this point it would be helpful to know what operational factors could influence the shape of the DMZ, thereby causing variation in angularity.

Variation Mechanisms

As mentioned above, asymmetries in flow directions cause distortions in feature angularity but do not cause variation. Variation in feature angularity is the result of physical factors which change the shape of the DMZ, causing changes in flow direction asymmetries. These factors, some of which were previously mentioned, may be present throughout the extrusion cycle and from billet to billet in a production run.

Lengthwise Variation

Variation in angularity along an extrusion is caused primarily by changes in the factors which affect the shape of the DMZ *during the extrusion cycle*. As outlined earlier,

localized temperature changes at the front of the billet and in the die, instability, and flow reversals are possible causes of variation along an individual extrudate. Die deflection, which may also vary throughout the direct extrusion cycle, could cause variation if the shape of the die aperture changes slightly (a recent study suggested that this factor is insignificant for small presses [Tashiro, 1992, p.196]).

Piece to Piece Variation

Piece to piece variation is caused primarily by changes in the factors which affect the shape of the DMZ *from billet to billet in a production run.* As identified earlier, changes in billet preheat temperatures (or, equivalently, varying dead cycle times between billets), steady changes in die temperature throughout a production run, and varying ram speeds from billet to billet may all be linked to variation in angularity.

Strategies for Improvement

The analytical study has answered the questions it sought to examine. The mental model it has produced provides a framework to use in thinking about the distortion in angularity and it has identified potential root causes for variations in angularity: namely, the factors which affect the shape of the dead metal zone. The task that remains is to identify what changes to the extrusion process should be tested in the experimentation phase of the project. Two generic strategies for improvement seem feasible. One could try to tightly control the process parameters which affect part variation, or, alternatively, one could try to find a way to decouple the final product from the varying process parameters, thus making the process more robust.

Improving Process Control

Although improving control over process parameters seems straightforward, it is actually a daunting task. Some important parameters such as die temperature are very difficult to measure, let alone tightly control. Furthermore, while the shape of the DMZ is influenced by process parameters, the simple fact that the billet becomes shorter as it is extruded is sufficient to change the shape of the DMZ. Therefore, it was not clear how much progress could be made, even if a large engineering project were launched to upgrade equipment controls.

Improving Process Robustness

Improving process robustness, on the other hand, seemed to be a more promising approach to controlling variation. Removing process parameters from the quality equation seemed simpler and cheaper than rebuilding the equipment. Relying on this strategy and using the mental model as a guide led to a focus on the geometry of the die entrance. The reason for this was that it seemed it might be possible to alter the die entrance in such a way as to separate the effects of the fluctuating DMZ from the friction forces at the die bearing. Thought experiments were conducted using the mental model to "test" various changes to the die entrance geometry. The most promising idea seemed to be creating a small "pocket" around the die entrance[2].

Symmetry provided the most convincing rationale for the pocket die. Fluctuations in the DMZ will cause nonparallel flow directions only in cases where there is asymmetry in the DMZ to begin with (cases where the distance to the container wall is greater on one side of the die opening than it is on the other side, see Figure 22 below). While proper die

[2] Although pocket dies are used by some soft alloy extruders in Europe, they are not commonly used in the U.S. The literature suggests using pocket dies for improved dimensional control over shapes which have thin-walled sections adjacent to thick areas, but it makes no mention of either positive or negative effects on angularity [Laue, 1976, p. 328].

design can sometimes be used to center die openings, the economic necessity of running multi-hole dies and certain geometric limitations usually force extruders to live with asymmetry in die layout.

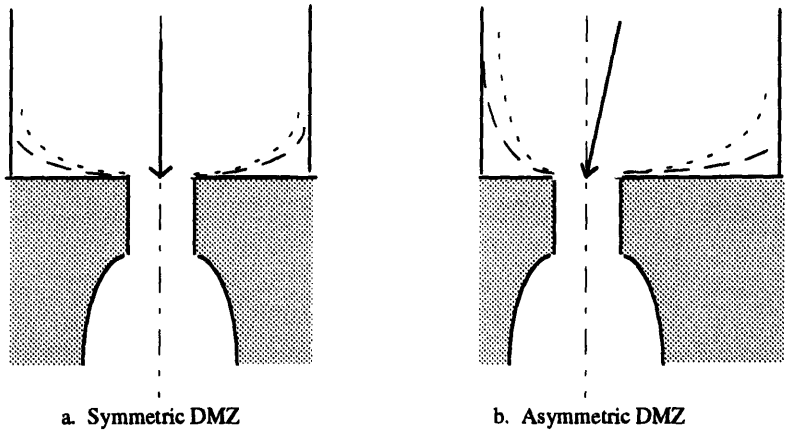
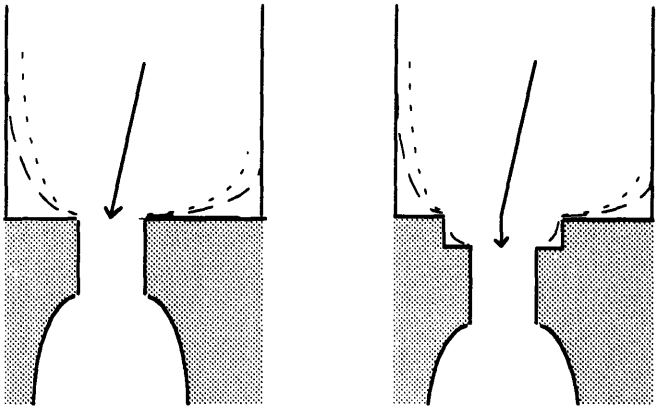


Figure 22. The Effect of Die Layout on the DMZ

Machining a pocket around the die opening, however, could provide a second chance to achieve symmetry, since the pocket would act as a "mini-container" (see Figure 23). A miniature DMZ would form in the pocket, further altering the direction of flow before metal reaches the die bearings. This time, however, the die designer could choose to create a symmetric miniature-DMZ that the metal would experience in the last stage of its trip to the die opening.



a. Flat b. Symmetric Pocket

Figure 23. The Pocket Die Control Strategy

Results

The analytical study was performed in a timely manner and incorporated many preliminary results from the data survey. Preliminary results from the analytical study were, likewise, incorporated into the planning of experiments in the third project phase, which overlapped with the second phase. This was a key factor in avoiding project delays due to the existence of fairly long lead times on experimental tool orders.

No attempt was made to perform an exhaustive study of the complex physical phenomena surrounding geometric distortions in extruded products. Instead, the study concentrated on developing a useful mental model which would capture the most important relationships that join process parameters to the quality of the final product. The experimentation phase of the project would provide an opportunity to further refine the model.

Chapter 5: Experimentation

Inspection alone does nothing to improve the quality of the product, and that product quality should be built at the production stage...build quality into the process.
Masaaki Imai, Kaizen

Experimentation is typically the most expensive phase of a process improvement project. While the investments made in the earlier phases tend to be weighted heavily toward the time of a few individuals, investments in experimentation usually include raw material, special tooling, and machine time in addition to the time of the practitioner(s). The key to using these resources efficiently is having good process data and a reasonably accurate mental model. The greater the practitioner's knowledge of the process *before planning experiments*, the higher the return will be on investments in experimentation. This is the reason the experimentation phase is placed last in the process improvement methodology.

Designed experimentation techniques are essential for maximizing the return on investments in experimentation. They enable the practitioner to minimize the number of runs necessary to examine the effects of multiple process parameters without resorting to the expensive method of changing one parameter at a time while keeping everything else constant. Performing an initial large-scale designed experiment (DOE) can be a good way to screen parameters so that cheaper, focused experiments may be used to zero in on the effects of the most important parameters.

Goals

In general, experiments should be performed to verify the mental model that has been previously developed and to test well-conceived measures to improve the process. These two objectives were difficult to separate in this study. The mental model identified changes in the shape of the DMZ as the link between fluctuating process parameters and variations in the feature angle in a final product. Simply varying machine settings and measuring the resulting effects on feature angles would not adequately test this model. Furthermore, the shape of the DMZ could not be explicitly used as a control factor in an experiment since it is the product of many factors and is not available for direct manipulation. The best method for testing the mental model, therefore, appeared to be using die geometry as a control factor which could alter the effect of changes in the shape of the DMZ on the final product. If the final product changed in accordance with predictions, the model would be verified. It was also believed that experiments to test the effect of changes in machine settings (billet temperature, ram speed, etc.) on the shape of the DMZ were unnecessary, since previous research had confirmed the existence of such relationships [Tashiro, 1992, p. 203].

The decision to use die geometry as a main control factor for testing the mental model was quite attractive, since the analytical study identified changes in die geometry as the most promising tool for reducing variation in the process. Thus it became possible to design a single experiment which could both verify the mental model and test an idea for improvement. If the experiment were to be successful, the remaining resources could be invested to further refine the improvement.

Equipment and Instrumentation

Experiments were performed on two extrusion presses that are sized for 6" diameter billets. These presses were chosen because they are the primary aerospace extrusion presses in the Plant, and because they are capable of producing extrusions with relatively large circle sizes. A large circle size is a desirable quality in an extrusion that is to be inspected with the digital protractor, since extrusions with small cross-sections are difficult to measure accurately.

Data collection is a critical part of conducting an experiment. It is important because it allows the practitioner to verify that the plan was followed correctly and because it can be used to monitor process parameters that may be important but cannot be tightly controlled. Finally, a complete record of relevant process parameters is extremely valuable in cases where the results of an experiment are not what the practitioner expected. Often, such results may be traced to unplanned fluctuations in control variables or noise factors. Without a complete record of the experiment, false conclusions might be drawn.

The standard press instrumentation was augmented by an ANAFAZE PC-based controller/data collection device for the purpose of this study. The following process parameters were monitored and recorded at ten second intervals:

Billet Temperature	(deg. F)
Container Temperature	(deg. F)
Die Temperature	(deg. F)
Exit Temperature	(deg. F)
Ram Speed	(in/min)
Ram Pressure	(psi)
Hydraulic Pump Stroke	(% of max)

Experiment 1 - Proving the Model

The first experiment that was performed was intended to verify the mental model and test the effectiveness of a pocket die in reducing variations in feature angularity. An important concern throughout the project was the robustness of any proposed process improvements. This is important because the Plant produces a practically limitless variety of shapes using more than 10 different alloys of aluminum. Furthermore, many parts are produced in small batches, making it necessary to perform frequent die changes and adjustments to machine settings. Any process improvement that is to be useful operationally would have to be effective in a wide range of conditions. This rationale also influenced the decision to pursue the process robustness strategy (making die modifications) rather than the process control strategy (preventing fluctuations in process parameters).

The robustness issue also influenced the decision to concentrate on Robust Design techniques in planning experiments rather than classical DOE techniques. The method that was chosen is described at great length by Phadke [Phadke, 1989]. It involves the use of a signal-to-noise ratio objective function along with Taguchi's orthogonal matrixes. The following factors were deemed important in the decision to apply Robust Design:

- it is based on Taguchi's quality loss function,
- it seeks to develop robustness against noise in the manufacturing process, and
- its objective function includes both the mean and the variance of the parameter in question.

Planning

Control Factors

The control factors that were chosen for Experiment 1 were:

2 Level	Die Geometry (flat, pocket)
3 Level	Butt Length (1", 1.5", 2")
	Alloy (7075, 7050, 2024)
	Billet Temperature (650° ± 50°)
	Ram Speed (1.8 in/min ± .4)
	Nitrogen Flow (off, low, high)

Degrees of Freedom

mean	1
1 two level factors	1
5 three level factors	10
1 2X3 interaction	2
total	14*

* four degrees of freedom remain for estimating the significance of each control factor.

Design Matrix

An L_{18} (2^1,3^7) orthogonal design matrix was chosen for Experiment 1. This matrix can accommodate up to 8 control factors (one two-level and seven three-level) and requires 18 runs of the experiment. The following table shows the design matrix that was used:

Experiment 1 Design Matrix

	1	2	3	4	5	6	7	8
billet	die geom	alloy	butt length	billet temp	ram spd	N2 flow	---	---
1	flat	7075	1"	600	1.4	off		
2	flat	7075	1.5"	650	1.8	low		
3	flat	7075	2"	700	2.2	high		
4	flat	7050	1"	600	1.8	low		
5	flat	7050	1.5"	650	2.2	high		
6	flat	7050	2"	700	1.4	off		
7	flat	2024	1"	650	1.4	high		
8	flat	2024	1.5"	700	1.8	off		
9	flat	2024	2"	600	2.2	low		
10	pocket	7075	1"	700	2.2	low		
11	pocket	7075	1.5"	600	1.4	high		
12	pocket	7075	2"	650	1.8	off		
13	pocket	7050	1"	650	2.2	off		
14	pocket	7050	1.5"	700	1.4	low		
15	pocket	7050	2"	600	1.8	high		
16	pocket	2024	1"	700	1.8	high		
17	pocket	2024	1.5"	600	2.2	off		
18	pocket	2024	2"	650	1.4	low		

Noise Factors

Several possible noise factors were identified before the experiment was performed. No special attempts were made to control these factors, since they are present to some extent in all production scenarios. The Robust Design philosophy discourages special noise control measures, since their presence will ensure that the optimum control factor levels will still apply in a production environment. The following items were considered to be potential noise factors:

Δ Die Temperature* (probable)
Δ Container Temperature* (unlikely)
Die Bearing Buildup/Erosion/Deflection (possible)
Δ Nitrogen Flow Rate* (unlikely)
Δ Billet Temperature (probable)

* Will be electronically monitored during experiment

Evaluation

Angularity data was collected using the digital protractor. Measurements were taken every foot over a 15-foot segment in the center of the 22-foot extrusions. The measurement points were marked so that the pieces could be reinspected if necessary with no loss of accuracy due to differing measurement locations.

The main objective function for this constrained optimization problem was to be the maximization of η, which is defined as $10 \log(\mu^2/\sigma^2)$, the decibel-scaled signal-to-noise ratio of the measured angle to its variance. This objective function was chosen due to the fact that it contains both the mean of angle measurements taken along each extrusion and the variance of the measurements. This is desirable since improving product quality involves both centering the manufacturing process and reducing variation about the mean. $-10 \log(\sigma^2)$ was also examined as an objective function.

Execution

Experiment 1 was performed using a tee-shape with a 4.000" stem, a 2.000" cap, and a uniform wall thickness of .094". Two new dies were used: a standard flat-faced die and one with a .250" wide x .375" deep pocket machined around the die opening. The bearings were identical on both dies (the pocket die had .375" less relief on the back of the die to compensate for the pocket on the face of the die). The dies were inspected by die repair personnel when they were received to check for manufacturing errors and any other differences between the dies that could mask the effect of adding a pocket to an otherwise identical flat die.

A six-control factor DOE is difficult to perform in a production environment. The skilled and patient operators at the Plant were a great asset in making sure that the special sensors and data collection equipment were installed properly and that the factor levels were carried out without any errors.

The 18 experimental extrusions were marked with the extrusion number, alloy, and die number on the cooling rack to avoid recording errors. When the experiment was over, the pieces were placed in a random order and the identifying inscriptions were covered so that the inspector could not identify the processing parameters that produced each of the pieces until the inspection was finished. These measures were taken to ensure inspector bias did not affect the results of the experiment.

Results

Raw Data

The raw data from Experiment 1 is shown in the tables, below:

	mean	stdev	var	n1 *	S/N **
	89.87	0.109	0.012	19.221	58.29
	89.90	0.074	0.006	22.587	61.66
	89.92	0.101	0.010	19.881	58.96
	89.95	0.139	0.019	17.162	56.24
flat die data	90.06	0.156	0.024	16.130	55.22
	89.96	0.205	0.042	13.746	52.83
	89.88	0.122	0.015	18.242	57.32
	89.82	0.113	0.013	18.910	57.98
	89.89	0.137	0.019	17.280	56.35

* - 10 log10 (variance)

** 10 log10 (mean^2/variance)

	mean	stdev	var	n1 *	S/N **
	89.44	0.076	0.006	22.334	61.36
	89.85	0.065	0.004	23.755	62.82
	89.46	0.081	0.007	21.796	60.83
	89.65	0.091	0.008	20.803	59.85
pocket die data	89.55	0.104	0.011	19.688	58.73
	89.71	0.098	0.010	20.191	59.25
	89.51	0.072	0.005	22.864	61.90
	89.30	0.077	0.006	22.304	61.32
	89.41	0.087	0.008	21.193	60.22

* - 10 log10 (variance)
** 10 log10 (mean^2/variance)

Analysis of Means

Figure 24 shows the analysis of means for the signal-to-noise (S/N) objective function. The higher the factor scored in the analysis of means, the lower the variation of angularity. Therefore, due to the additive property of the S/N objective function and orthogonal matrixes, one could minimize variation by choosing the highest scoring level for each control factor. This analysis clearly shows that the pocket die performed better than the flat die. The analysis of variances must be consulted, however, to determine which control factors are statistically significant.

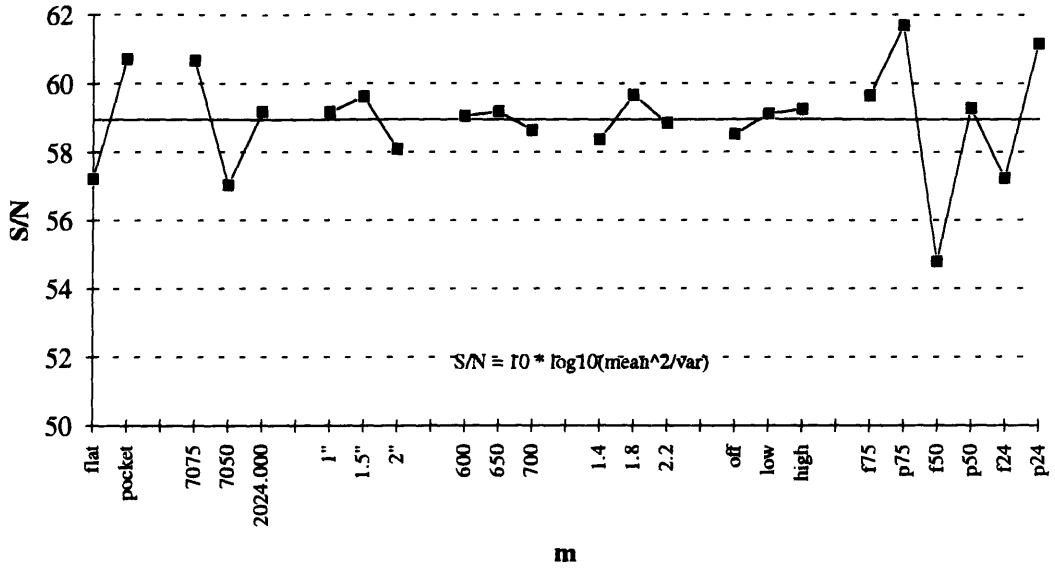


Figure 24. Experiment 1 - Analysis of Means

Though the main objective function was chosen in the spirit of Taguchi, an Analysis of Means using $-10 \log(\sigma^2)$ as an objective function yielded the same results as the signal-to-noise objective function. This implies that the variance response also contains the essential information which describes the process. Therefore, a two-step improvement process involving the use of the experimental results to reduce process variance coupled with existing die repair techniques to center the process on the desired nominal value should be feasible.

Analysis of Variances

The analysis of variances for the signal-to-noise ratio objective function (shown in the table below) indicates that only two experimental factors are statistically significant: die geometry and alloy (the F-test cutoffs are 7.71 and 6.94 for 1 degree of freedom and 2 degrees of freedom factors, respectively). This analysis indicates that the experiment has

successfully verified the mental model and seems to have proven the value of the pocket die in reducing variation in angularity.

Experiment 1 S/N ANOVA

	SS	DoF	MS	F
die geo	54.92	1	54.92	82.62
alloy	40.12	2	20.06	30.17
butt length	7.60	2	3.80	5.72
billet temp	1.01	2	0.51	0.76
ram speed	4.98	2	2.49	3.74
nitrogen	1.77	2	0.89	1.33
geo x alloy	5.04	2	2.52	3.79
error	2.71	4	0.68	
total	118.1476	18		

The interaction between die geometry and alloy (which can be calculated from the first two columns of the L18 orthogonal matrix) does not seem to be significant. This interaction would be very important if the impact of pocket die were found to vary from alloy to alloy. Figure 25, a plot of the interaction terms, indicates that even if it were statistically significant it would be very small since the two lines are basically parallel.

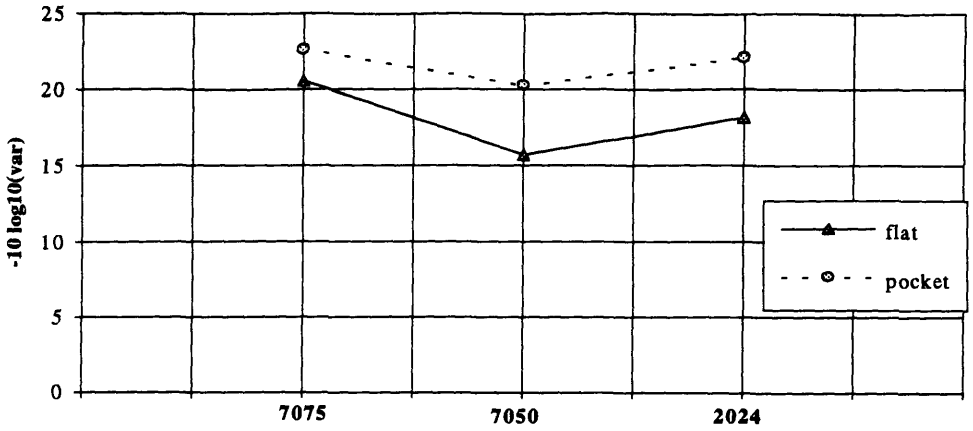


Figure 25. Experiment 1 - Interaction Terms

Economic Considerations

A regression study was conducted using exit temperature data from Experiment 1 (see Appendix G: Regression Analysis of Experiment 1). The resulting model suggests that the pocket die adds approximately 29° F to the exit temperature of the extrudate. Likewise, a 1.0 in./min. increase in ram speed adds roughly 49° F to exit temperature, and a 1.0° F increase in billet temperature adds .2° F. Each individual alloy also affects exit temperature by a few degrees. This finding is important because it can be used to estimate the effect of a pocket die on press productivity. This is possible because an excessively high exit temperature will cause problems with surface quality in some alloys. This limits the maximum exit temperature that can be achieved, placing a limit on ram speed, and, consequently, press productivity. The tradeoff, then, is the reduction in ram speed that is necessary to offset the temperature rise caused by the pocket die. The magnitude of the reduction in ram speed can be estimated by:

$$\left(\frac{29 \text{ degrees F}}{49 \text{ degrees F / in. per min.}}\right) = .59 \text{ in / min.}$$

This factor could reduce press productivity by <10% to 30% depending on the ram speed that would be normally achieved with a flat die and the percentage of downtime inherent in the job (due to setup and dead cycle time). This is a pessimistic estimate because it assumes that the press would be operating at the maximum ram speed with the flat die and that compensating factors such as a reduction in the billet preheat temperature could not be used (for instance in cases where a colder billet temperature is not feasible due to the inability of the press to initiate extrusion using the harder billet material). Furthermore, it does not take into account the expense of scrapped parts (which can easily add 20-30% to the cost of running a small job), die repair work, and rework in the finishing area. When all factors are considered, a pocket die may actually reduce the total cost to produce a lot. This is a likely scenario considering that pocket dies are recommended only in cases where a hard-to-control critical angle cannot be economically produced to acceptable quality levels with conventional extrusion and rework practices. Additional experience with pocket die technology, however, will be needed before a full economic assessment can be made.

Conclusions

The following conclusions were made concerning Experiment 1:

- The mental model is correct.
- The pocket die reduced variance by 55% over the flat die for a centered, symmetric tee-shape (or, equivalently, reduced standard deviation by 33%).
- The analysis of variance indicates that die geometry and alloy are significant at a 95% confidence level.

- At the speeds and temperatures covered by the experiment, 7075 had the least variation in feature angularity and 7050 had the most. 7075's standard deviation was 66% of 7050's and 2024's standard deviation was 77% of 7050. This observation agrees with common perceptions at the Plant.

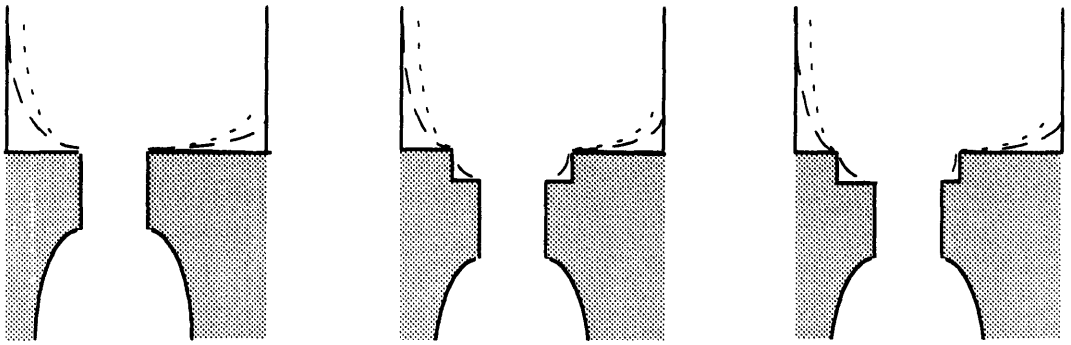
- Similarities between the analysis of the $-10\ \mathrm{Log}(\sigma^2)$ and $10\ \mathrm{Log}(\mu^2/\sigma^2)$ objective functions imply that the log function is a reasonable transformation of the data.

- Residual plots show the error in the model to be reasonably random.

Experiment 2 - Pushing the Limits

While Experiment 1 appeared to be very successful, a verification experiment (at the optimum factor levels) is necessary to confirm that the additive model is adequate [Phadke, 1989, p. 60]. Furthermore, testing the pocket die concept on a different shape would increase confidence that the method applies universally.

The initial idea to test a pocket die came from observations about symmetry in the analytical study. It was surmised that creating a symmetric "mini-container" could counteract the effect of asymmetry in the DMZ in the container. This proved to be successful in Experiment 1. An extension of the same logic would imply that an asymmetric pocket around the die opening could do even more to counteract asymmetry of the DMZ if the asymmetry of the pocket were in the opposite direction as the asymmetry in the DMZ (see Figure 26, below). It was decided to expand the scope of the verification experiment to test this theory as well.



a. Flat b. Symmetric Pocket c. Asymmetric Pocket

Figure 26. Experiment 2 - Die Geometries

Planning

It was decided to use an "L" shaped angle with a long leg of 3.560", a short leg of 2.750", and a wall thickness of .100" for Experiment 2. The lack of symmetry in the shape was attractive since it would cause even more asymmetry in the DMZ. Furthermore, the die was laid out in such a way that the die opening was shifted toward the edge of the die. This would accentuate asymmetry in the DMZ. Three new dies were ordered for Experiment 2: a standard flat die, a symmetric pocket die (.250" wide x .375" deep all the way around the die opening) and an asymmetric pocket die (.125" wide x .375" deep on the interior of the angle and .375" wide x .375" deep on the exterior of the angle near the edge of the die). Once again, the dies were carefully inspected upon receipt.

A designed experiment was not needed in this case since die geometry was the only factor under investigation. All other factors were to be held constant. The plan was as follows:

1. Run six billets with the flat die at standard billet and container temperatures and whatever ram speed is necessary to achieve an 840° F exit temperature.

2. Run six billets with the symmetric pocket die at standard billet and container temperatures and the ram speed established in step 1.

3. Run six billets with the asymmetric pocket die at standard billet and container temperatures and the ram speed established in step 1.

It was hoped that this testing procedure would provide verification for the results of Experiment 1 (by comparing the results of steps 1 and 2) and then push the limits of the technique by adding results for an asymmetric pocket die to the comparison.

2024 was chosen as the test alloy and the press was wired for data collection as it was in Experiment 1.

Execution

Experiment 2 experienced difficulties from the beginning. Both the flat die and the asymmetric die experienced a problem with waviness in one of the legs of the angle. This problem, which is common in these types of shapes having long, thin legs, is due to non-uniform flow velocities as was discussed in Chapter 4. Die repair personnel worked repeatedly on the dies, using techniques which are known not to affect feature angularity. After some time it was decided to pull the flat die and the asymmetric pocket die and rerun them with Experiment 3. This would give die repair more time to make corrections. While this problem sounds severe, it should be kept in mind that new dies often require such attention from die repair.

Results

When the flat die and the asymmetric die were finally run with Experiment 3, it was found that the symmetric pocket die reduced the variance of feature angularity by 80% over the flat die. This result was reassuring. The fact that the symmetric pocket die

performed even better than the pocket die in Experiment 1 was not surprising. The mental model suggests that asymmetry in the DMZ would be a bigger problem for the shape used in Experiment 2 than the shape used in Experiment 1. Therefore, one might expect the flat die performance to be worse in Experiment 2. If the symmetric pocket is able to dampen out the effect of fluctuations in the DMZ to the point where other factors drive variation in angularity, one would expect a greater amount of variation reduction in Experiment 2.

The asymmetric pocket die did not perform well. The extrusions produced with the asymmetric pocket die exhibited signs of feed-in from the surface of the billet and a contour problem on one of the legs. The poor quality of the extrusions made the test inconclusive. It was felt that the die design may have been too aggressive. The high degree of asymmetry in the asymmetric pocket die (which was designed to ensure that the results of the two types of pocket dies would differ significantly) coupled with the off-center layout of the die opening caused extremely asymmetric material flow patterns to develop within the billet. The resulting instability of metal flow near the die opening may have caused the distortion of the extrudates which invalidated the results of the experiment. A lesser degree of asymmetry should be used in any future tests.

Experiment 3 - Further Optimization

Experiment 1 indicated that die geometry and alloy were the only significant control factors. This result does not mean that all of the other factors are unimportant; rather, it indicates that the effects of die geometry and alloy were so strong that they overshadowed the effects of other, weaker factors. As one addresses the stronger factors that arise from a DOE study (adopting pocket dies, for instance), the weaker factors suddenly become significant from a process improvement standpoint. They become the

new levers that one may use to further optimize the process. Experiment 3 was planned with this goal in mind.

Planning

The plan for Experiment 3 was to run a pocket die and vary billet temperature and ram speed to determine if these process parameters would have an effect on variation in angularity when the other parameters (including die geometry) are fixed. Three factor levels were to be used for each variable in order to identify nonlinearities in the response. This necessitated the use of a Taguchi L9 matrix. The design was as follows:

Billet #	Billet Temp.	Ram Speed	<Empty>	<Empty>
1	650	2.0	---	---
2	650	3.0	---	---
3	650	4.0	---	---
4	625	2.0	---	---
5	625	3.0	---	---
6	625	4.0	---	---
7	600	2.0	---	---
8	600	3.0	---	---
9	600	4.0	---	---

When problems were encountered with the flat die and the asymmetric pocket die in Experiment 2, it was decided to try to use the asymmetric pocket die in Experiment 3 after making repairs. This would minimize the amount of die preparation, the number of experimental runs, and the number of die changes that would be necessary.

Execution

As was previously mentioned, the asymmetric pocket die did not perform well in Experiment 3. The symmetric pocket die could not be made ready on short notice, so it could not be used when the asymmetric pocket die failed.

Results

The results of Experiment 3 were inconclusive. The contour problems and waves that were encountered at every factor level destroyed the character of the data (see the ANOVA table below). It would have been redone using the symmetric pocket die if time had permitted.

Experiment 3 ANOVA Table

	SS	DoF	MS	F
Billet Temp	22.23	2	11.1	1.15
Ram Speed	29.20	2	14.6	1.52
error	38.55	4	9.6	
total	89.98	8	11.2	

Experiment 4 - The Effect of Heat Treat

The data survey pointed out that it was not possible to inspect any production lots immediately after heat treat since it is necessary to stretch heat treated metal very soon

after quench. Experiment 4 used the extrusions that were produced in Experiment 1 to examine the effect of heat treat and stretch on variation in angularity.

Planning

The plan for Experiment 4 was very simple. The effects of the heat treat and stretch operations would be individually evaluated by inspecting the test lot from Experiment 1 immediately after heat treat and again after stretch. This was made possible by the fact that the pieces were not part of a production lot; hence, they could be scheduled for heat treat whenever it was convenient for inspection without regard for the shipping schedule. Furthermore, achieving the correct metallurgical properties was not critical since the pieces would not be shipped to a customer.

Execution

The pieces were already inscribed with the billet number, alloy, and die number, and the press inspection points were marked on each extrusion at one foot intervals. The experiment mainly required measurement and data analysis.

Results

The standard deviations of the angle measurements along each piece for each of the three processes are listed in the table below. In addition, average standard deviations are given for the pocket die extrusions and the flat die extrusions after each process.

Press, HT, and Stretch Standard Deviations

Billet	Press	HT	Stretch
1	0.11	0.05	0.10
2	0.07	0.23	0.10
3	0.10	0.30	0.12
4	0.14	0.23	0.17
5	0.16	0.14	0.11
6	0.21	0.18	0.10
7	0.12	0.14	0.13
8	0.11	0.13	0.13
9	0.14	0.13	0.13
10	0.08	0.16	0.06
11	0.06	0.27	0.10
12	0.08	0.14	0.06
13	0.09	0.17	0.13
14	0.10	0.06	0.04
15	0.10	0.11	0.13
16	0.07	0.09	0.06
17	0.08	0.05	0.06
18	0.09	0.05	0.09

Average Standard Deviations:

	Press	HT	Stretch
flat	0.13	0.17	0.12
pocket	0.08	0.12	0.08

From the average standard deviation summary, it is obvious that heat treat and stretch have roughly equal and opposite effects on variation in angularity. Heat treat, on average, increased the standard deviation of the angle by .04 in both the flat die case and the pocket die case. Stretch reduced the standard deviation by a like amount, so the final variation after stretch is roughly the same as the variation at the press. This result verifies the assumptions that were made concerning heat treat and stretch in the Production Processes section of the Data Survey.

The effects of heat treat, stretch, and the combination of heat treat and stretch can be seen in Figs. 27 through 29, below. Each graph is a cross plot showing the upstream process on the X axis and the downstream process(es) on the Y axis. 1:1 correlation lines are included to indicate where the points would lie if the process on the Y axis had no effect on variation. From the graphs one can easily see that, in general, heat treat increases variation (on average the points lie above the 1:1 line) and stretch decreases variation (the points generally lie below the 1:1 line). The heat treat/stretch combination graph shows the points to be fairly evenly distributed about the 1:1 line, indicating that the two processes roughly cancel one another out.

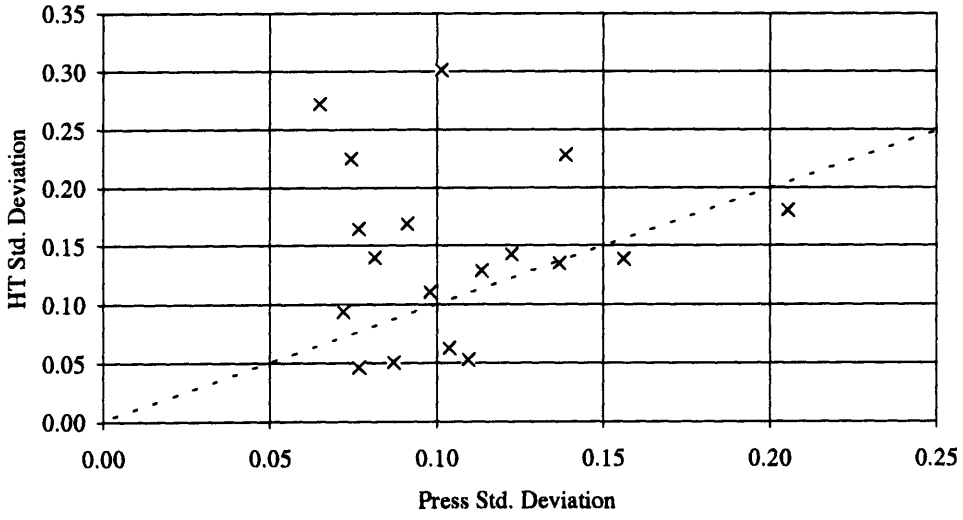


Figure 27. The Effect of Heat Treat on Variation

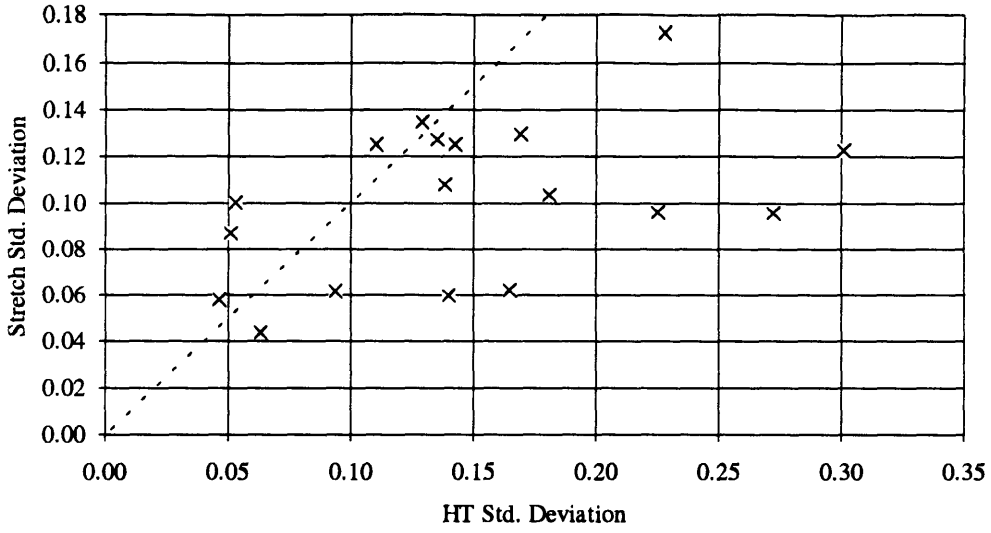


Figure 28. The Effect of Stretch on Variation

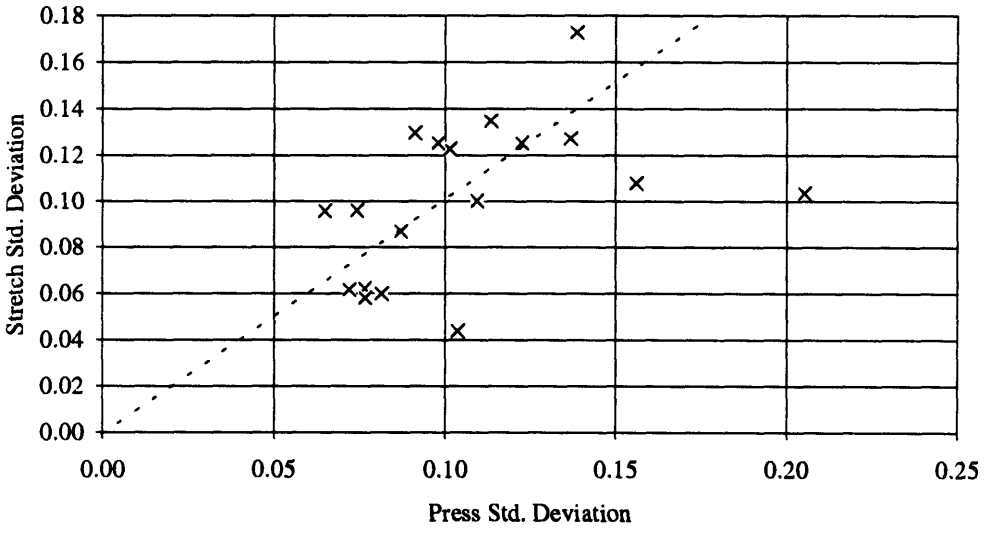


Figure 29. The Effect of HT and Stretch on Variation

Figure 30, below, shows the effect of the three processes on an individual extrusion. While heat treat has had a large effect on this piece, stretch has removed much of the variation so that the end result is close to the variation that was measured at the press.

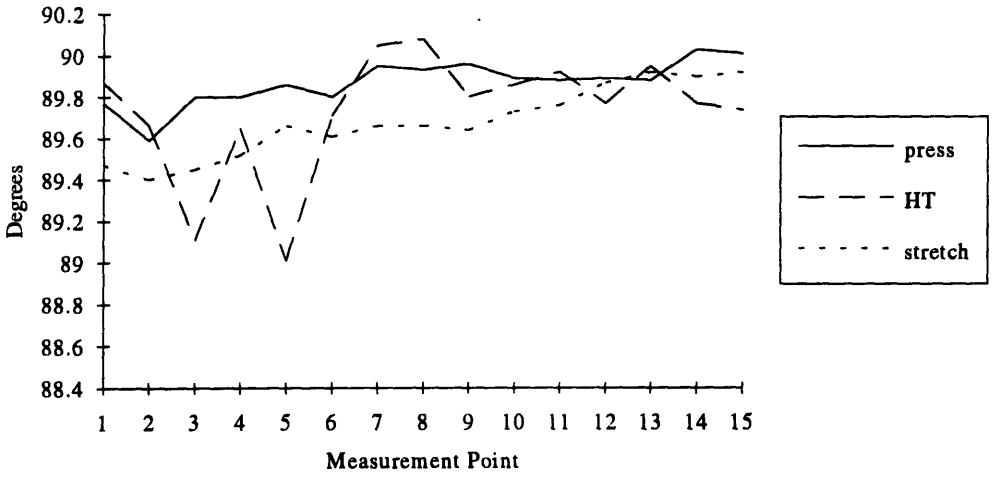


Figure 30. The Effect of HT and Stretch on an Individual Extrusion

Experiment 4 confirmed the decision to address the extrusion process first in the process improvement project. It also implies, however, that the heat treat process remains as an additional opportunity for improvement.

Chapter 6: Results and Recommendations

Results

The results of each phase of the project have been documented in detail in the relevant sections of Chapters 3, 4, and 5. Chapter 6 is intended to serve as an executive summary of the project's findings.

Data Survey

- Front, middle, and back measurements are adequate for characterizing the mean and variance of a production lot for test purposes. Front and back measurements would be sufficient for routine production inspections if the number of pieces is relatively large ($n \geq 10$?). Experimentation requires greater accuracy since, in many cases, a single extrusion is used to evaluate a given set of operating parameters. Measurements were taken every foot in this study.

- Variation in angularity did not vary in a predictable way along individual extrusions. Likewise, raw angle measurements exhibited no trends along individual extrusions.

- Variation in angularity is positively correlated with aspect ratio and circle size, and negatively correlated with distance from the shape to the edge of the die.

- The extrusion process has the greatest effect on variations in angularity of the final product. Heat treat increases variation and stretch reduces variation. The effects roughly cancel in heat treated lots. Other processes have very little effect on

angularity.

- the Plant's production system is statistically capable at current industry standards for angularity. Process improvements will be necessary, however, to produce parts to half industry tolerances or less without the need for expensive inspection and rework.

- Achieving very tight tolerances (under $\pm$ 1.0°) will require adjustments to both the mean and the standard deviation of the manufacturing system. Routine die repair techniques already exist for adjusting mean angles.

Analytical Study

- A reasonable mental model for describing variations in angularity hinges on the shape of the dead metal zone. Local asymmetries in the slope of the dead metal zone cause metal to flow into the die opening in directions which are not parallel to the intended runout direction (which is perpendicular to the face of the die). The resulting impingement of metal upon one of the die bearings creates an imbalance between the friction forces at the two die bearings, causing the feature to exit the die in a direction which is not parallel to the intended runout direction. The angle between said feature and adjacent features (which, perhaps, exit parallel to the intended runout direction) will be distorted, and not correspond to the angle machined into the die. Variations in factors which influence the shape of the dead metal zone become fluctuations in the level of distortion experienced by the feature angle, translating into variations in angularity.

- The mental model led to a strategy of increasing the robustness of the extrusion process to changes in the shape of the dead metal zone. Two changes to the geometry of the die opening, the symmetric pocket die and the asymmetric pocket die, were proposed for

experimentation.

Experiment 1:

- verified the mental model's assertion that die opening geometry and variation in angularity relate to one another through the influence of the dead metal zone. It further demonstrated that the effect of die opening geometry overwhelms the effects of changes in the other control variables.

- demonstrated the effectiveness of the pocket die in reducing variation in angularity. The symmetric pocket die reduced the variance of feature angularity by an average of 55% (or, equivalently, reduced the standard deviation of feature angularity by 33%).

- observed no statistically significant interaction between alloy and die geometry.

Experiment 2:

- verified the results of Experiment 1 by demonstrating that, the symmetric pocket die reduced the variance of feature angularity by 80% (or, equivalently, reduced the standard deviation of feature angularity by 55%).

- did not produce any inspectable parts using the asymmetric pocket die due to contour problems and waviness.

Experiment 3:

- proved to be inconclusive due to problems with the asymmetric pocket die (described above under Experiment 2).

Experiment 4:

- demonstrated that heat treat and stretch have roughly equal and opposite effects on feature angularity. Heat treat increases part variation and stretch decreases variation. The net result is a level of variation that is approximately the same as the variation that existed at the press.

Recommendations

The results of this study suggest six areas for further investigation and/or implementation at the Plant:

1. Adopt symmetric pocket die technology on a trial basis.

The symmetric pocket die has proven its usefulness in two experiments. It is now ready for further testing on production orders. A good strategy might be to order both pocket dies and flat dies for special orders which have tight-tolerance critical angles. This way a standard flat die will be available if difficulties are experienced with the pocket die. Filling these jobs with flat dies would require extra expense in any case, so that the additional effort required to apply the new technology will not necessarily add any incremental expense to the order. The experience and knowledge gained in production tests, however, could prove to be quite valuable

2. Continue experimenting with variations on the symmetric pocket die.

The asymmetric pocket die did not perform well. The pocket design and the shape that were chosen were intended to be very aggressive. This was done to provide a clear

distinction between the results of the symmetric pocket die and the asymmetric pocket die. A more conservative design (less asymmetry in the pocket and a layout which is centered better on the die) could prove to be an improvement over the symmetric pocket die. Knowledge gained in these studies might also be applied in the development of new repair techniques for pocket dies.

3. Continue to pursue repeatability improvement projects.

The data survey demonstrated that the variation in angularity along the extrusion dominates total variation within a production lot. Even so, part-to-part variation is very important. Fortunately, the effect of a pocket die (decoupling variation in the final product from changes in the shape of the dead metal zone) apply equally well to process parameters which vary during the extrusion cycle and those which vary between consecutive extrusion cycles. Reductions in part-to-part variation, however, would further improve overall product quality as determined by the control of critical feature angles.

4. Consider investigating the effect of the heat treat process on angularity.

While the heat treat process is less significant than the extrusion process in determining the variation in feature angularity of the final product, its importance will grow as improvements to the extrusion process reduce its relative contribution to total variation. A study of the heat treat and quench cycle could, potentially, yield large benefits in the effort to better control critical angles.

5. Study the effect of detwist on angularity

A decision was made early in the data survey to bypass this operation due to resource constraints. It may be significant, however, in cases where certain shapes typically require a great deal of rework to correct problems with twist. Suggestions were made in the data survey for ways to study this unconventional process.

6. Build upon the knowledge that was developed in this study.

The policy recommendations and the process improvement methodology that resulted from the study should be seen as starting points for future investigations, not conclusions to a project. Mental models have a short shelf life. They soon lose their usefulness if they are not questioned and refined. Likewise, the real power of a methodology is that it is merely a place to begin, a set of tools and strategies which cause the user to think about *how* a problem is solved rather than *what* must be done to solve it. A methodology must be taken off the shelf and challenged occasionally if it is to help a practitioner or an organization hone their problem-solving skills.

capabilities. Placing an emphasis on the creation of a mental model is a unique and powerful feature of this methodology.

Resource Efficiency

Another significant difference between this process improvement methodology and others is the way it focuses on resource efficiency. This is a critical factor in production environments where all resources are limited. A firm that can squeeze more benefits out of its process improvement resources than its competitors are capable of will make the same improvements with lower investments or achieve larger gains for the same investments. Either outcome can be parlayed into a strategic advantage in the marketplace.

Resource efficiency is addressed by the methodology in two ways: by forcing the practitioner to address allocation issues early in the project, and by structuring the project in such a way that synergy can occur between seemingly disconnected, self-contained project steps.

Resource Allocation

The resource allocation feature of the methodology worked well in this project. Thinking about resource allocation in the pre-project planning period and scheduling investments for all phases of the project simultaneously brought many important questions to mind, such as:

Chapter 7: Methodology Evaluation

The preceding text described the features of the process improvement methodology and the successes and failures of the test case that was performed to evaluate its suitability for use in a manufacturing production environment. The following critique is intended to document those features of the methodology which worked well, and to identify some improvements that could make the methodology more robust against the types of difficulties that were encountered during this project.

Effectiveness

All process improvement methodologies must ultimately be evaluated on the basis of their effectiveness in reducing costs or improving product quality. This methodology succeeded in producing a tangible, credible recommendation for reducing the variation in feature angularity. The immediate value of this recommendation will be greatly influenced by decisions made by Plant management regarding implementation, and by the success of Plant personnel in addressing operational issues associated with the implementation of the new technology. Additional benefits can be obtained, however, from the mental model which was built to help make a connection between process data and process physics. While in the short run the mental model is used primarily to stimulate thought regarding modifications of the process, it can also have significant long term benefits. This will occur if the mental model gains sufficient exposure to influence the organization's perceptions of the process. In such cases, an enhanced knowledge of the process will improve operational decision making and lead to a greater understanding of system

- When would the help of an assistant be most beneficial?
- How much time can be safely invested in data collection?
- What needs to be accomplished before experimentation can begin?
- How long will it take to analyze the results of an experiment?
- If only one experiment could be performed, what should it be?
- What resources are being overlooked?

These questions helped to create a coherent strategy for resource usage, increasing the probability that each resource would be used in the phase(s) of the project to which it was best suited.

The resource allocation step also facilitated the early identification of tradeoffs. One such tradeoff came from an observation that data collection, which primarily requires a time investment on the part of the author, could be substituted for experimental data, which requires the investment of valuable press time. Additional time was, therefore, allocated to data collection in the belief that a larger number of data points would illuminate trends, enabling the mental model to predict a process "fix" which would have a high probability of success. This reduced the need for expensive press experiments and led to the identification of the pocket die as a tool which could provide better control over feature angles.

Synergy

If process improvement resources are to be used with maximum efficiency, the project must be balanced in such a way that every part plays a critical role in the success of the endeavor and no part could have been omitted without sinking the project. While there was a small measure of redundancy in this project, there was also a definite feeling throughout the study that each phase would have to be executed very well if the project

were to yield any useful recommendations. Each phase relied on other phases for direction and confirmation to the degree that an error in one phase could cause the others to go astray. This interdependency is the essence of synergy. It enables the practitioner to make better decisions in each of the phases, reducing the investment that is required to improve the process. Figure 31 shows some of the information flows between the project phases which ensured that learning from one phase would be fully utilized in the other phases.

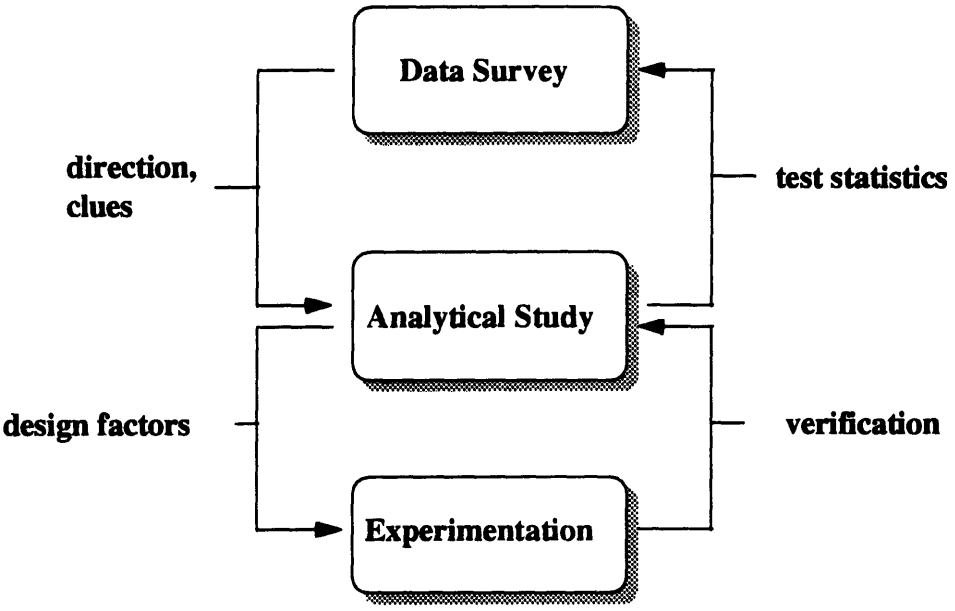


Figure 31. Project Synergies

The analytical study began when preliminary results from the data survey indicated that the extrusion process has the greatest effect on the variation of the final product. The analytical study also took clues from early correlations between variation in angularity and geometric factors, giving it a head start in constructing a reasonable mental model. As the

analytical study progressed, it predicted other geometric correlations (for instance, standard deviation vs. extrusion circle), which were then examined and confirmed by the data survey. This transfer of information between the data survey and the analytical study ensured that the developing mental model was firmly grounded in reality, and reduced the amount of time and effort necessary to build an understanding of the extrusion process.

The analytical study continued after the experimentation phase began. The process knowledge that was developed in the first two phases of the project was a critical factor in formulating an experimentation strategy that was focused, yet capable of both verifying the mental model and testing the most promising idea for improvement in a single experiment. This factor alone greatly reduced the necessary investment in experimentation. In addition, insights developed by the analytical study were used to determine the control factors for Experiment 1 and led to the use of special instrumentation to monitor potential noise factors. Experiment 1 verified the mental model from the analytical study, indicating that it is a fair representation of reality. This result facilitated the switch in focus from understanding the extrusion process to identifying and testing ideas for process improvement. Resources were redeployed without delay.

Areas for Improvement

The process improvement methodology was designed for implementation in a case where the practitioner had no prior experience with the manufacturing process. As such, the project began with a lengthy data collection phase which was necessary to create a familiarity with the process as well as to build a database for statistical analysis. In many cases, the practitioner will have a solid basis of experience with the process under study or access to useful historical data. In such cases, it may be helpful to begin with the

analytical study in which the practitioner uses prior knowledge to construct the initial mental model which is then used to direct a very focused data survey. If the data confirms the mental model, the investigation can turn to experimentation. In all cases, the structure of the project must take advantage of all available resources, especially prior knowledge.

The biggest disappointment in the project was the failure to attain useful information from the asymmetric pocket die. This incident was a byproduct of the lean nature of the methodology. The methodology achieves efficiency by reducing redundancy in effort and discouraging investments that are not essential to the success of the project. This strategy can backfire if an unforeseen problem occurs at a key point in the project (such as the failure of the asymmetric pocket die due to an overly aggressive design). A detailed risk management plan should, therefore, be added to the methodology to deal with this possibility. This plan, which should be done in conjunction with the resource allocation step, should list the critical factors in the project that could become "show stoppers" if a failure were to occur. Next, an appropriate level of redundancy must be planned. For example, in this project, the failure of a die or the data collection equipment during an experiment would both be considered show stoppers. In the case of a die failure, perhaps two or three dies of slightly different designs should have been ordered and made ready for use so that a failure of the most aggressive die would not wreck the experiment.

It should be stressed again that flexibility is the key to maximizing the return on resources invested in improving manufacturing processes. This principle applies as well to the planning of operational details as it does to high-level project planning. The proper application of flexibility is what enables one to do more with less.

Je plie et ne romps pas
"I bend and I break not"
Jean De La Fontaine (1621-1695)

Appendix A: Charts and Graphs

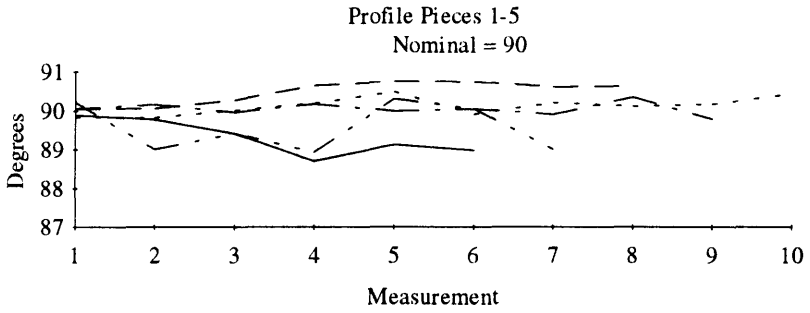


Figure 1.

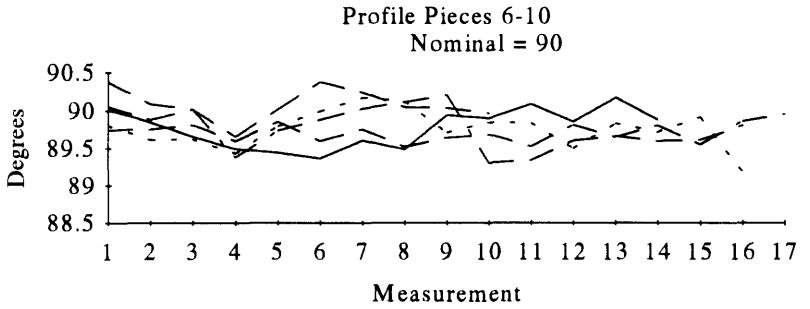


Figure 2.

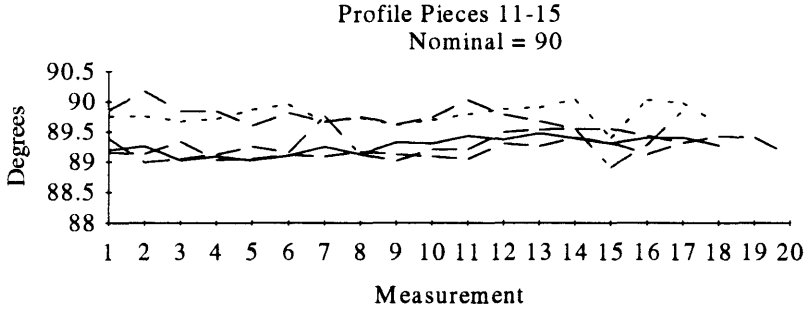


Figure 3

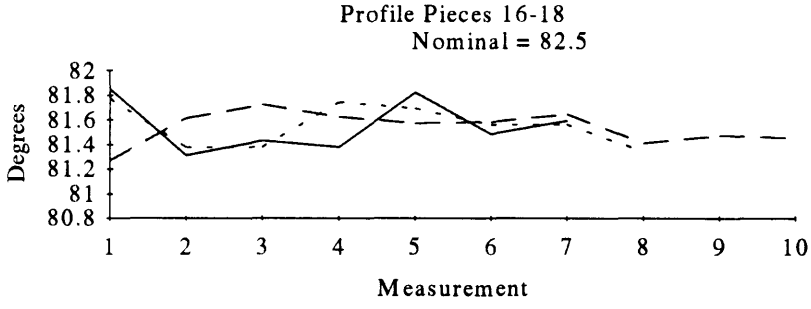


Figure 4

Appendix B: Angularity Measurement Procedures

General Guidelines:

Look for >= 25 billet, one hole jobs.

Keep track of bad contour measurements and the general configuration of the contour.

Front/back only measurements may be OK if necessary (Sutton stretch), but try to get at least 3 measurements per piece.

At each step in the process fill in the relevant section of the **Angularity Data Sheet**.

At each step in the process, draw the shape's cross-section and label the dimension measured.

Re-zero the instrument every time you adjust the blade length.

Always check/use the decimal setting on the protractor.

Use blade blocks whenever possible.

Check to make sure the measurement increases with increasing angle, make a note of any negative angles.

Sampling Guidelines at the Press:

Take measurements at 3 evenly spaced points (front, center, end) for "full length" extrusions.

Take measurements at 5 evenly spaced points for pieces that will later be cut in half.

Take front and back measurements at least 24" from the rough cut to avoid measuring the mat'l that will later be scrapped.

Sampling:

Job Size (pcs)	Frequency
<= 40	all
>40	every other

Mark the front end of symmetric shapes for identification at later stages (to preserve data on variation trends, and to identify which side to measure on symmetric pieces, etc.).

Take 3 pieces per job and measure every 12" for "profile pieces".

Carefully draw the die face and the orientation of the hole(s).

Sampling Guidelines Downstream:

Take three point measurements.

Randomly sample the same number of pieces checked at the press (usually 50% of entire lot).

Keep track of which measurements are fronts and which are backs.

Take 3 pieces per job and measure every 12" for "profile pieces".

Calculations:

* If ≥ 5% of the pieces measured have bad contour, repeat the calculations leaving out all of the pieces which have any bad contour measurements.

Perform calculations per **Angularity Calculation Sheet**

Preliminary Analysis:

Compare grand means for each lot.

Compare lot standard deviations.

Check normality of each lot (and mean=median)?

Check if Salong is approximately equal to Salong for profile pieces.

Check if $(\text{Salong})^2 + (\text{Sbetween})^2 \approx \text{VARall}$.

Compare number of bad contour pieces by lot

Appendix C: Sample Angularity Data Sheet

General

Shape		Alloy	
Die Number		Temper	
Lot Number		Thick/Thin	
Customer		Aspect Ratio	
Nominal Dimension		# Billets Planned	
Tolerance			

Press

Date Extruded		Ram Speed	
Shift		Nitrogen	
Press/Container		Operator	
# Holes		Collector	
Billet Temp		Runout Length	
Billet Length		Ext. Ratio	
Container Temp		Exit Temp	
Die Temp (?)		Metal Temp	
Measurements Taken		Die Repairs	
Datafile Name		# Data Points	

Stretch

Date Stretched		Operator	
Shift		Metal Temp	
Stretcher		Plugs	
Stretch Goal		# Data Points	
Measurements Taken		Final Step?	
Datafile Name			

Roll

Machine Used		Operator	
# Rollers		Leg, # of Passes	
Measurement Taken		# Data Points	
Datafile Name		Final Step?	

Detwist

Machine Used		Operator	
Measurement Taken		# Data Points	
Datafile Name		Final Step?	

Appendix D: Sample Angularity Calculation Sheet

Date _____ Sketch:

Part Number _____

Lot Number _____

Operation _____

	All Pieces Sampled	W/O Bad Contour
grand mean [average(Xi)]	_____	_____
standard deviation [stdev(Xi)]	_____	_____
variance [var(Xi)]	_____	_____
min, median, max	_____	_____
skewness	_____	_____
kurtosis	_____	_____
Salong [average(Si)]	_____	_____
Sbetween [stdev(X-bari)]	_____	_____
estimated variance	_____	_____
Salong for profile pieces	_____	_____
	_____	_____
	_____	_____
mean	_____	_____
number of pieces with bad contour	_____	
general location	_____	
Cp / Cpk	_____	_____

Appendix E: Confidence Interval for Variances Along and Between Extrusions

A log transformation will cause variance data to appear to be approximately normally distributed. The resulting data, may then, be used to compute a confidence interval for the difference between the variances for the two sets of data.

	Along			Between		
	Stdev	Var	-Log(Var)	Stdev	Var	-Log(Var)
1	0.124	0.015	1.813	0.096	0.009	2.035
2	0.306	0.094	1.029	0.177	0.031	1.504
3	0.123	0.015	1.820	0.095	0.009	2.045
4	0.098	0.010	2.018	0.080	0.006	2.194
5	0.273	0.075	1.128	0.106	0.011	1.949
6	0.192	0.037	1.433	0.172	0.030	1.529

sample mean	1.540	1.876
sample variance	0.165	0.084

Comparing the sample means of the transformed variances:

$$\mu_1 - \mu_2 : \bar{x}_1 - \bar{x}_2 \pm z(\alpha/2)\sqrt{\frac{S_1^2}{n_1} + \frac{S_2^2}{n_2}}$$

confidence interval for a difference in means

$$\mu_1 - \mu_2 : 1.876 - 1.540 \pm (1.645)\sqrt{\frac{.165}{6} + \frac{.084}{6}}$$

$\alpha = .100$ for a 90% two-sided confidence interval

$$\mu_1 - \mu_2 : (.001, .671)$$

The confidence interval does not include zero, therefore, the mean of the transformed variances describing variation between extrusions is greater than the mean of the transformed variances describing variation along the individual extrusions to a 90% confidence level. To put this into perspective, if the transformed variance between extrusions is 1.876, the transformed variance along the extrusions will fall in the range of (1.877,2.547) with a 90% certainty. Taking the inverse transform of these values yields the following result:

variance between = .0133 degrees squared, and

variance along = (.003,.0132) degrees squared.

$$\% \text{ of variance between } = \left(\frac{.0132}{.0133}\right), \text{ and } \left(\frac{.003}{.0133}\right)$$

at the endpoints of the confidence interval. This implies that, to a 90% level of confidence, variance along will be between 23% and 99% of variance between.

Appendix F: Variance Reduction in Experiment 1

Flat			Pocket		
stdev	var	-log(var)	stdev	var	-log(var)
0.109	0.012	1.921	0.076	0.006	2.222
0.074	0.006	2.222	0.065	0.004	2.398
0.101	0.010	2.000	0.081	0.007	2.155
0.139	0.019	1.721	0.091	0.008	2.097
0.156	0.024	1.620	0.104	0.011	1.959
0.205	0.042	1.377	0.098	0.010	2.000
0.122	0.015	1.824	0.072	0.005	2.301
0.113	0.013	1.886	0.077	0.006	2.222
0.137	0.019	1.721	0.087	0.008	2.097
sample mean		1.810			2.161
sample variance		0.058			0.020

Taking the inverse transformation of the sample means yields a mean variance of .0069 degrees-squared for the pocket die and .0155 degrees-squared for the flat die. This reveals a reduction in variance of 55% for the pocket die, or, equivalently, a reduction in the standard deviation of 33%.

A 95% confidence interval for the difference in means for the two die geometries clearly shows that μ_1, the pocket die mean, is greater than μ_2, the flat die mean. This translates into a lower variance for the pocket die when the inverse transformation of the data is performed to the limits.

$$\mu_1 - \mu_2 : \bar{x}_1 - \bar{x}_2 \pm z(\alpha/2)\sqrt{\frac{S_1^2}{n_1} + \frac{S_2^2}{n_2}}$$

confidence interval for a difference in means

$$\mu_1 - \mu_2 : 2.16 - 1.81 \pm (1.96)\sqrt{\frac{.058}{9} + \frac{.020}{9}}$$

$\alpha = .050$ for a 95% two-sided confidence interval

$$\mu_1 - \mu_2 : (.168,.533)$$

Appendix G: Regression Analysis of Experiment 1

Data from the 24 billets that were extruded in Experiment 1 (18 test billets and 6 billets that were used to test the equipment and heat the tooling) were used in a multiple-regression study to examine the effects of processing parameters on exit temperature. Six parameters were used in the first run of the model but two of them, container temperature and nitrogen flow, were dropped from the model when they proved to be insignificant. The variables which remain are:

billet temperature	(in deg. F)
ram speed	(in in./min.)
die geometry	(0 = flat, 1 = pocket)
alloy	(2024, 7050, 7075, a 1 means the alloy was used)

The model was generated using the LINEST() function of Microsoft Excel V. 2.0a. The summary table is shown below.

Regression Table

	alloy24	alloy50	alloy75	pocket	ram	billet	intercept	
	708	702.8723	710.6522	28.69279	49.14567	0.205111	-190.134	Coeffs
	2.57E+08	2.57E+08	2.57E+08	4.544805	5.616679	0.054663	2.57E+08	Std Err of Coeffs
r^2	0.890676	10.81598						Std Err of Y est.
F	23.08356	17						Degrees of Freedom
Sum Sq.	16202.62	1988.75						
	reg.	residual		9.588714	11.85017	0.118092		

F.025,6,17= 2.698656
t,.025,17 = 2.109819

The r^2 value of 0.89 implies a reasonably good fit of the data, and the F value of 23.08 (which is greater than the test statistic of 2.699) indicates that the model has significance at the 95% confidence level. The bottom row of the table shows the test statistics for die geometry, ram speed, and billet temperature that were calculated by multiplying the standard error of the coefficients by t,.025,17. The fact that the coefficients are greater than the test statistics suggests that they are all statistically significant at the 95% confidence level.

Appendix H: Confidence Interval for Experiment 2

A log transformation will cause variance data to appear to be approximately normally distributed. The resulting data, may then, be used to compute a confidence interval for the difference between the variances for the two sets of data.

	Flat Die			Pocket Die		
	stdev	var	log(var)	stdev	var	log(var)
	0.263	0.069	1.160	0.192	0.037	1.433
	0.302	0.091	1.040	0.167	0.028	1.555
	0.501	0.251	0.600	0.125	0.016	1.806
				0.282	0.080	1.100
				0.109	0.012	1.925
				0.108	0.012	1.933
sample average		0.137	0.933		0.031	1.625
sample variance			0.087			0.107

Comparing the sample means of the transformed variances:

$$\mu_1 - \mu_2 : \bar{x}_1 - \bar{x}_2 \pm z(\alpha/2)\sqrt{\frac{S_1^2}{n_1} + \frac{S_2^2}{n_2}}$$

confidence interval for a difference in means

$$\mu_1 - \mu_2 : 1.625 - .993 \pm (1.96)\sqrt{\frac{.087}{3} + \frac{.107}{6}}$$

$\alpha = .050$ for a 95% two-sided confidence interval

$$\mu_1 - \mu_2 : (.205, 1.059)$$

The confidence interval does not include zero, therefore, the mean of the transformed variances for the pocket die is greater than the mean of the transformed

variances for the flat die at a 95% confidence interval. To put this into perspective, if the transformed mean variance for the flat die is .993, the transformed mean variance for the pocket die will fall in the range of (1.198,2.052) with a 95% certainty. Taking the inverse transform of these values yields the following result:

flat die variance = .102 degrees squared, and

pocket die variance = (.009,.063) degrees squared.

reduction = flat die variance - pocket die variance, so,

$$\%\ \text{reduction} = \left(\frac{.102-.063}{.102}\right) = 38\% \qquad \text{and} \qquad \left(\frac{.102-.009}{.102}\right) = 91\%$$

This implies that, to a 95% confidence level, the pocket die could reduce variation by as little as 38%, or as much as 91% over the flat die.

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