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Optimize Stress in Roll Forming

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Optimize Stress in Roll Forming

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Abstract

In an effort to supply tooling designers with more accurate data the effects of tooling design on final product variation were investigated. Redundant Deformations were citied as the main source of variation in tooling design. Experiments were carried out to investigate and add to the body of knowledge of this claim.

1 Table of Contents

2 Introduction

This MQP was a research project, and as such the bulk of this report focuses on the background research required before experiments could finally be carried out. Much research was carried out in metal forming, roll forming, metallography, and microstructure analysis. The research is useful in understanding the scope of the problem, as well as identifying areas ready for further investigation.

Roll forming is not yet well understood and is often referred to as a "black art" by the few texts that deal with the subject. The motivation to start the project draws from a desire to take the art out of roll forming and bring it into the realm of predictability and repeatability. Unfortunately, the reason roll forming is still regarded as a black art is because there are so many variables involved in the process. It will take a lot of time and effort to understand how all of these variables interact and affect each other.

It was very difficult to simultaneously research roll forming and metallography techniques while also trying to learn the art of sample preparation and imaging. We consider the mistakes we made and corrected as valuable information for future groups who may pursue their goals using the same tools. As such, there is much discussion in the report about preparation procedures and metallographic procedures. The appendices contain detailed procedures that will allow future groups to quickly start in the right direction.

Our experimental results only comprise a small portion of this report: a reflection of the time spent researching compared to time spent experimenting. Some results were obtained, but more experiments need to be performed to validate our conclusions.

This report was written with a future group in mind, trying to present enough information to get someone quickly up to speed on the factors involved.

3 Purpose

One of the goals of CIS is to produce higher quality products with less dimensional variation. One way to accomplish this goal is to improve the roll forming process capability. Currently, roll forming tooling is designed with the help of finite element analysis software, but stress levels predicted by the software are not always accurate. The aim of this project was to identify real stresses in a work piece. With a better understanding of the real behavior of the work piece, the engineers will design tooling which would produce more consistent parts.

An overview of the goals and the variables associated with this project is presented in Figure 1. The project team was initially divided into two teams which would investigate factors affecting roll forming system stability and product stability. Much research was conducted under these two categories and the topics are noted on the lower levels of the tree. Eventually, a goal for the project was established. The relationship of this project goal to the overall goal of CIS is indicated with a red line.

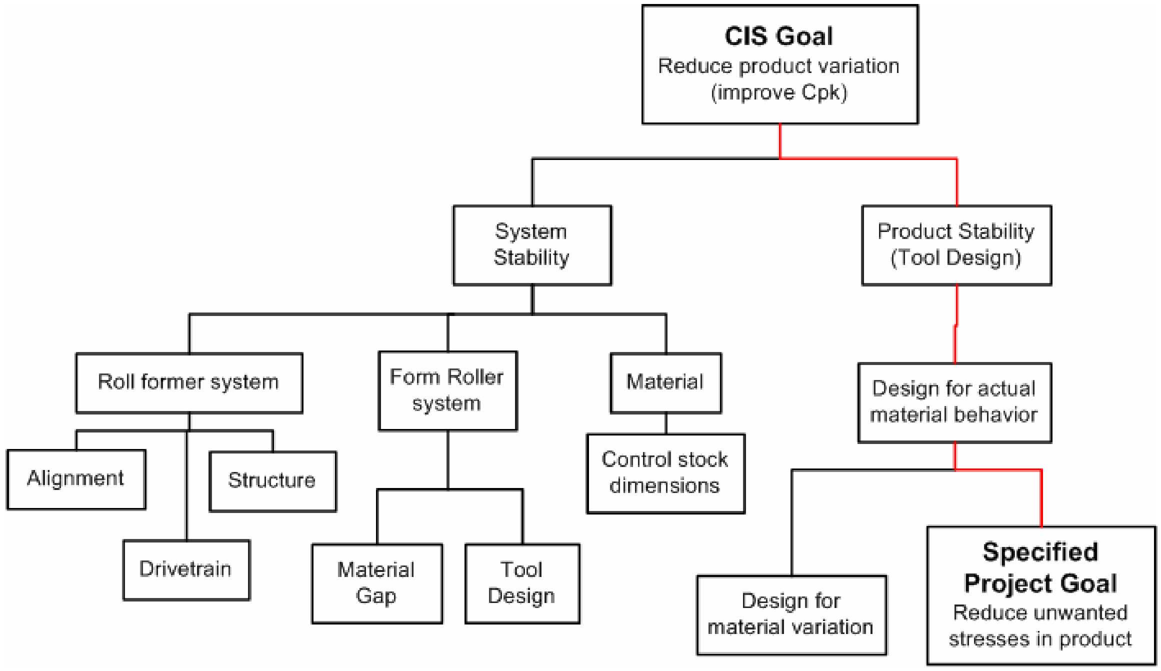

Figure 1: Project overview chart

4 Roll Forming Background

4.1 Metal Forming

Metal forming is a category of manufacturing processes that rely on plastic deformation of metal to produce a part. Metal forming processes are "chipless", that is, they do not remove volume as in machining or milling. As chipless processes, metal forming operations produce less waste.

Basic metal forming operations are classified into several groups [1]:

- Rolling
- Extrusion
- Drawing
- Sheet Forming
- Forging
- Shearing/Piercing

Most of these categories describe *bulk deformation* processes, that is, a process whereby the small surface area to thickness ratio of a part is changed by deformation so that the ratio increases. For example, the deformation of a solid ingot into a thin sheet is a bulk deformation process.

Sheet forming, Drawing and Shearing/Piercing are processes whereby a relatively large surface area to thickness ratio remains unchanged throughout the forming process, generally called *sheet forming*. For example, the deformation of a flat strip iron into angle-iron is a sheet forming process.

Processes categorized under bulk deformation or sheet forming:

Bulk Deformation Processes	**Sheet Forming Processes**
• Rolling • Extrusion • Forging	• Bending • Pressing • Stamping • Drawing/Deep Drawing • Spinning • Shearing

4.1.1 Sheet Forming

Sheet forming is a process where metal sheet is formed without changing its surface area to thickness ratio. A type of sheet forming, sheet roll forming or roll forming as it will be referred to from this point onward, involves the use of profiled rolls to bend and form sheet metal. The roll forming process is capable of producing continuous lengths of cross section. Roll forming is usually a cold-forming process, that is, the process temperature to melting point ratio is less than 0.3:

$$\frac{ProcessTemperature}{MeltingPoint} < 0.3$$

Cold forming processes require more force than hot forming processes where the previous ratio is greater than 0.6. Cold forming processes produce more dimensionally accurate parts with better surface finish, and better mechanical properties. The good surface finish on cold rolled cross sections results in better corrosion resistance. The stock metal can be painted or galvanized before being rolled because cold forming produces a good surface finish and the forces required to bend a thin sheet are small.

Bending requires consideration of the *minimum bend radius* of the particular metal being worked. The minimum bend radius prevents fracture, or cracking, in the bend which would otherwise lead to a defective bend. A quality bend is free of unsatisfactory surface conditions such as: fracture, indenting, necking, wrinkling, galling, or folding. In general, soft metals require a smaller bend radius than hard metals: generally a minimum bend radius of 1/32-inch to 1*T is a good starting point for soft metals; some soft metals can be bent on themselves or effectively a zero bend radius without any ill effects. A good starting point for hard metals is 2*T to 3*T where T <1/16" (T = thickness of metal being bent) [2].

Factors affecting the formability of a material include ductility, a biaxial stress condition, the condition of the edges bounding the bend, and to some extent the orientation of the sheet being bent. An increase in ductility will cause a decrease in the minimum bend radius. Ductility can be increase by locally heating the bend, or by applying uniform (i.e. hydrostatic) pressure to the metal around the bend [3]. A biaxial stress condition develops fully as the length of the bend increase past about 10 times the thickness of the metal. Biaxial stress happens when there is tensile stress on the outer surface of the bend, as well as tensile stress axial with the bend, that is, along the length of the bend. On the inner surface of the bend, the biaxial condition is compression around the bend, and tension along the bend. Biaxial stress increases the minimum bend radius. In the uniaxial condition, where the length of the bend is relatively short, the material will neck down in the axial direction around the bend. As the bend radius to material thickness ratio (R / T) decreases, narrow sheets (L < 10*T) crack at the edges, and wider sheets (L ~ 10*T) crack in the middle – the location of highest biaxial stresses.

Edge conditions also affect formability. Rough edges bounding the bend will increase the minimum bend radius because cracks and surface irregularities act as stress risers, propagating edge cracks into the bend. Cold working the edge by shearing will also increase the bend radius because cold working reduces the ductility of the edge, resulting in cracks in the bend along the edge.

Sheet orientation affects formability by increasing the chances of cracking in the bend in certain directions for cold rolled sheet. Cold rolling orients the grains of a metal, as well as inclusions in the material matrix, known as mechanical fibering. Ductility of the metal is decreased in the transverse direction, and hence the minimum bend radius is increased in the transverse direction (with the grain).

4.1.2 Springback in Sheet Forming

Springback is the elastic recovery of the metal after being plastically deformed. A springback factor K was created to characterize springback. Springback can be compensated for by: over bending, coining, stretch bending, or localized heating.

Over bending is the most common practice, it compensates for springback by bending the material more than necessary so that it springs back to the desired dimensions. Coining subjects the bend to intense localized compressive stresses so that tensile stresses around the outside of the bend are relieved. Stretch bending, where the sheet is stretched and then pulled over a form to create the bend, reduces the non-uniformity of stresses in the bend. Localized heating increases the ductility of the metal in the bend, and allow the structure to relax and reset.

4.2 Roll Forming Design

Roll forming like many manufacturing processes may at first appear simple, but designing a process that is repeatable requires adequate knowledge of the mechanisms behind the process. The following is a brief overview of one particular method for developing a roll forming process. Several mechanisms that are important to the process are discussed.

The first step in roll forming design is the development of a cross-sectional drawing of the part to be manufactured. The cross-sectional drawing shows a cross-section of the part at an angle perpendicular to the parts directions of travel through the rollers. This drawing includes many important dimensions most importantly those of the bends, the material thickness, and the straight dimensions. Other important information to note are the existence and location of any pre-notching, pre-cut lengths, multiple gauges, and combination sets. These will play an important role in determining the amount of bending per pass. This cross-section is the main dimensioning the only dimension not drawn is the length of each piece. This cross-section helps determine the progression of bending passes.

Once the cross-sectional drawing has been completed the original strip width should be calculated. The most important part of this process is choosing the correct K-factor so the proper bend allowance can be calculated [4]. The K-factor is the percentage of the material thickness, starting from the inside edge of a bend, that the neutral axis lies on. When metal sheet is bent the material on the inside of the bend is compressed while the material on the outside of the bend is stretched from the tension applied to it. The neutral axis is the axis where the material remains its original length. Figure 2 gives a good representation of this phenomenon.

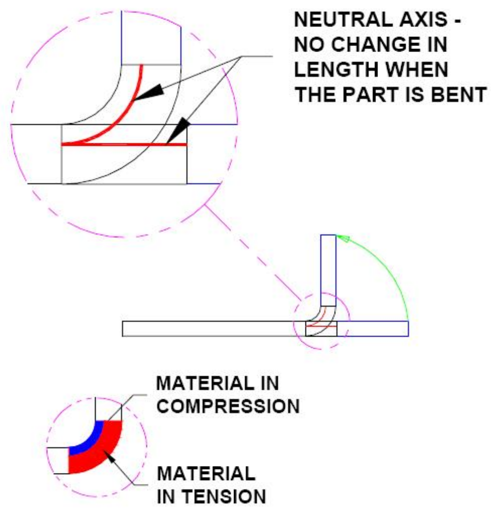

Figure 2: Forces and neutral axis in a bend [5]

Since the length of the neutral axis does not change, knowing its length will allow the original width of the material to be calculated. The material on the inside of the bend is shorter than it was before the material was bent, using the inside radius measurement alone will therefore result in a part that is too long. Using the K-factor the proper Arc Length can be determined, which is given by the following equation:

$$ArcLength = \frac{(insideradius * K * T) * \ finishingangle * \pi}{180^{\circ}}$$

In this equation T represents the thickness of the material and the finishing angle is the final angle of the bend. The K-factor is mainly dependent on the geometry of the bend, the yield strength of the material, and the material type.

Once the strip width and thickness have been selected a bend progression flower should be generated. This is the point when each step in the bending process is originally calculated. When trying to determine the bend sequence the positioning of the rollers should be taken into account. For instance, on a typical C channel bend, pictured in Figure 3, the outside or second bend is bent first, but is often not closed. This allows an extra pass with the inside roller on bend one [4].

Figure 3: Bend planning [4]

If there is pre-punching on bend two then it is best to close bend two before starting bend one, this will reduce distortion [4]. In conjunction with the bend flower a chart based on the flower can be generate to show the degree of each bend per pass in table form. This will show exact degree of bending per pass more clearly than writing directly on the flower drawing. The amount of over forming should also be taken into account when determining the bend progression.

The amount of bending done at each pass is a very important factor in the formation of the flower pattern. The amount of bending done at each pass weighs heavily on the stresses caused by bending the material. The distance between each roll forming station, the roll diameters, and any side rollers or guides will also affect the amount of stress added into the material. The determination of how much bending should be done is the main focus of this project and the main factors will be discussed in later sections.

Once the flower pattern is complete the next stage of design is to check for any clearance issues between the rollers and the incoming metal. Also the pitch diameters should be decided, these are often increased progressively throughout the process to prevent from binding of the metal. The pitch diameter refers to the largest roll diameter that contacts the part, it is the part of the roller which has the greatest tangential velocity and thus is the part that moves that pulls the part forward. Increasing the pitch diameter assures that the part is being pulled from station to station.

Once tooling layout has been determined it can be decided if any special tooling accessories should be incorporated into the process. Tooling accessories like guides, side rolls, and straightening devices can be added to the process during this portion of design. Straightening devices are normally used towards the end of the process either on the last pass or between the last two passes in the case of precut strips. Straightening devices help smooth out any unwanted twists in the part [4]. Side rolls are those placed on the vertical axis perpendicular to the main rollers these often to aid the metal entering the first forming sets of rollers and to reduce side to side movement of the sheet material during rolling.

This design process has been written as a step by step process, but the process is an iterative one; each step does not end when the other begins, if a problem is found within the design it must be fixed and the process reworked. There are now many software programs to aid in the design of a roll forming process. These programs may help provide the designer with visualizations of the process as well as provide some quantitative data. However, these programs work on the same principles discussed in this section and are not a replacement for understanding the process, but an aid in process development.

4.3 System Stability

System stability refers to the consistency of the roll forming machine. Variation in the dimensions of the machine could contribute to variation in the final part.

The system is broken down into several components, listed below.

- Material (usually strip stock)
- Strip Stock Straightener (to remove coil-set, not always used)
- Entry Guide (to align strip with the roll form tooling)
- Roll Formers (the structure supporting the roll form tooling)
- Roll Forming Tooling (the surface over which the strip is bent)
- Lubrication System (lubricates the interface between strip and tooling)
- Drive train (provides power to the rollers)
- Part Straightener (straightens the part after the final forming stage)
- Cutoff Die (cuts the part to length)

The components that most likely contribute the most to system variation are highlighted in Figure 4. Detailed information on the highlighted subjects can be found in Alvarez [6] and Nickel [7].

Dimensional variation in the final part usually stems from variations in material thickness and the material gap between male and female rollers. Controlling or accounting for the dimensional variation on the stock material should reduce dimensional variation on the final part. The alignment of the roll formers to their mates and to other stages will affect the material gap and the tracking of the part down the line, respectively. The deflection of the roll former structure under load will also affect the material gap: the roll formers and roll forming tooling will deflect most toward the centerline of the work piece, as predicted by bending theory. The tooling design needs to account for expected variation in the material gap as well as variation in the material thickness in order to meet tolerances for the finished part. A general list of some important points is compiled in the appendix, section 9.1. It should be useful for students looking for a quick overview that can guide future research.

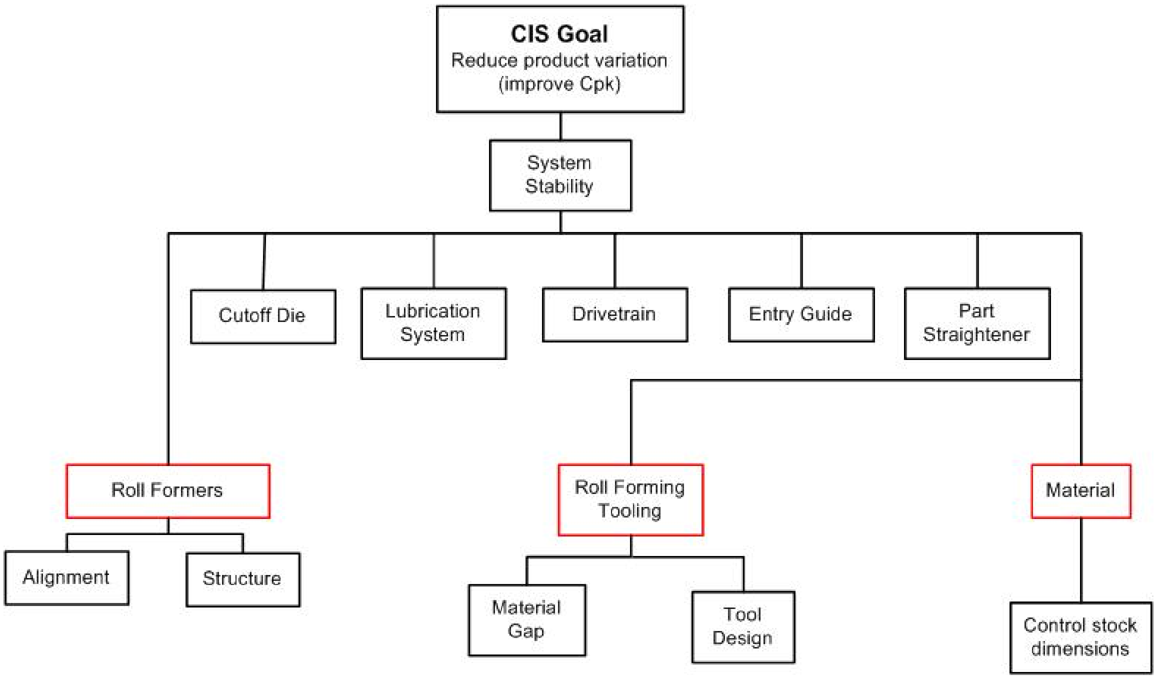

Figure 4: Component breakdown of the roll forming system. Components that most likely contribute the most to system variation are highlighted.

4.4 Tool Design

Once a design has been developed and put into place it is almost inevitable that there will be problems in the finished product, especially if the designer does not have access to adequate design tools. In roll forming this is often the case. In almost every book on roll forming or expert that is consulted it is almost inevitable roll forming will be referred to as a "black art." From the tooling design side this is only the case because the process can often be complex to model theoretically and there is little data on the actual stress distribution in the process. In his doctoral paper written in 2005, Michael Lindgren states that CAE programs often take too long to design and compute to be of any use in the industrial side of roll forming [6]. At this stage they are most useful in furthering basic theoretical assumptions of roll forming programs like PROFIL. Perhaps once more modeling has been done on the theoretical side programs like PROFIL will be more accurate in their modeling of stresses, so that designers may have to rely less on "experience" of this "black art". The second way to improve the designer's knowledge is to measure the actual stresses that are occurring in the part. The second is of most interest to this project.

The cause of the unwanted stresses must be clear in the designers mind before a thorough design can commence. There are three types of stresses that will cause defects because of inadequate design considerations these are stresses at the rollers on the part or transverse bending, problems from tracking, and stresses cause by the geometry of the process. The forces at the rollers could be a buckling issue or a stress that is too large and exceeds the yield strength. Problems from tracking issues indicates that the part has "slipped" sideways during forming and bending is occurring in a position it should not be, thus putting stresses in places they should not be. The geometry of the process causes the material being bent at the rollers to affect the material between roll stages. These may form if stresses at the rollers are not causing problems or if either of the first two cases is occurring.

For the stresses at the roller caused by the transverse bending to be unwanted more deformation than was designed for must be caused. One type is a buckling issue, for this to happen a column of material must be force along its longitudinal axis. This issue should be considered when designing the flower pattern and can be corrected by adjusting the progression. A tooling design text by Alvarez shows a good example of this condition [6]. The second type results from over cold working of the material. If the radius is too tight for a given material cracking or buckling occurs. This indicates that the designer did not account for the proper amount of cold work the material can withstand. Both of these conditions should be visible through a visible inspection of the part and if edge cracking cannot be determined macroscopically it can be detected microscopically.

If stops are used on the rollers than the material can only slip side to side when it has a width less than the designed for width. While design of the rollers can help stop tracking from occurring tracking problems are often a variation in material problem and thus a concern of system stability.

The third type of unwanted deformations can cause noticeable defects in the part. Unlike deformations at the roller however these types of deformations will have causes that may not be as obvious. This does not mean that their causes are not understood, for instance excessive longitudinal deformation may cause bow in the part. If a roll progression has twelve stations, it may be difficult to pin point which station(s) caused this to happen. Furthermore it may not be obvious why dimensions are varying within a part. If a combination of defects is occurring and it is not obvious on a macroscopic level that the part is bowing or twisting it is hard to determine where these deformation are occurring within the finished part. These deformations require considerable investigation.

4.4.1 Redundant Deformations

To understand the where stresses arise from during forming some terms need to be defined. The direction that the material flows in is the longitudinal direction, while the direction perpendicular to this is the transverse direction. The position of the material in question can be at the roller or in between roll stations, up stream would refer to material that has not yet entered a certain roller and down stream would be material that has traveled past a roller. All forming at the roller is in the transverse direction, thus Halmos refers to this as transverse bending [9]. There is also a second type of deformations that could arise; these are due to stresses caused by the geometry of the process. In a typical bending operation two dies bend the entire work piece at once, that is there is no material adjacent the bend line. Bending takes place throughout the whole part at once. In roll forming one cross-section is bent at once while the rest of the work piece is attached up and down stream from the roller. The metal directly adjacent to the forming metal is now being stressed by the metal in the roller and the metal outside of it and so on. As Lindgren observed: longitudinal stress is maximum immediately before the roller and decreases greatly the farther upstream the material is [8] (Lindgren built a U-channel model that was able to correlate a longitudinal strain relationship with known physical data from several other authors.) This would indicate that the metal that is not in the roller namely the material upstream is being stress because of the geometry of the operation.

These unwanted stresses can cause unwanted deformations, which will from here on be called redundant deformations. As redundant indicates these are unnecessary stresses for the forming of the part, while a deformation indicates that these are permanent. While these stresses are caused by the nature of the process and cannot be eliminated, the stresses can be reduced to a level that will not cause permanent deformation. In a quantitative sense this means that stresses must not reach a level that is greater than the yield stress of the material. Once the yield stress is exceeded the metal will be permanently deformed.

Redundant deformations are classified by the direction of their influence and then their specific influence on the metal. Halmos defines five types of redundant deformations: longitudinal bending and bending back, longitudinal elongation or shrinkage, transverse elongation or shrinkage, shear in the metal's plane, and shear in the metal's thickness [9]. Several of these are detailed in Figure 5 below. From this base any distribution of stress can broken down into these five components.

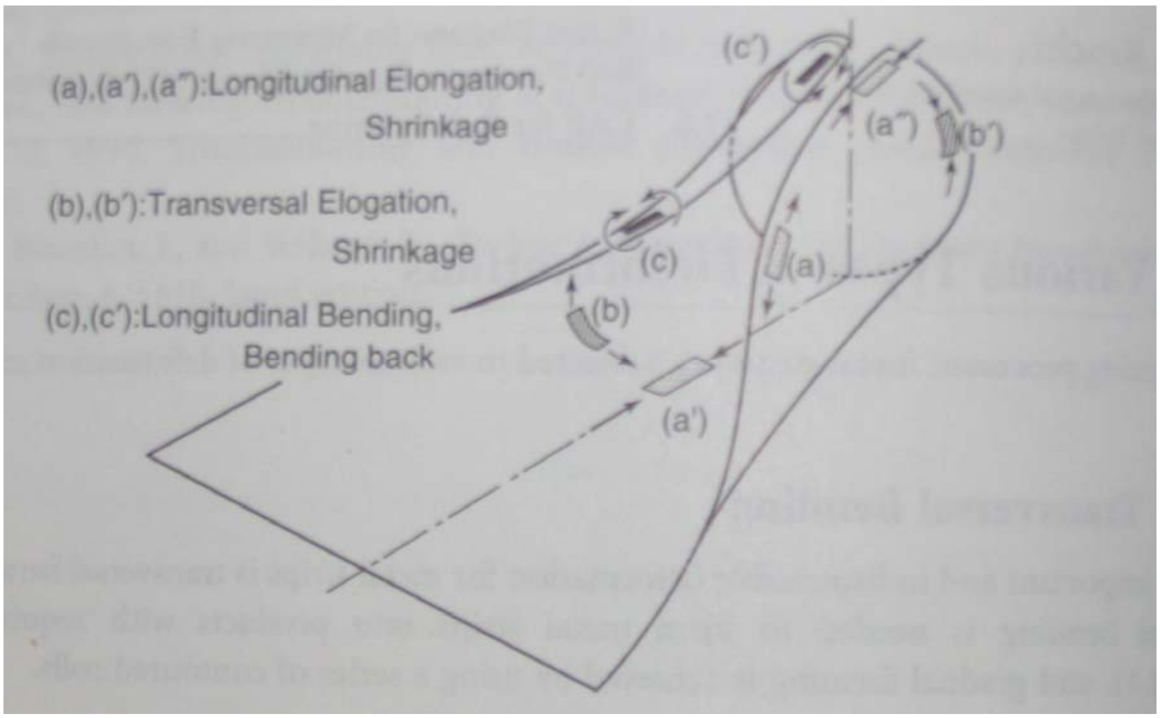

Figure 5: Redundant deformation definitions [9]

Selecting the Right Materials

To understand, the criteria for selecting materials for a process it is first necessary to understand what material properties the process depends on to function. As with any forming of metal, roll forming depends on the plastic deformation of a metal to allow the metal to retain its bent shape. Temperature has a huge effect on how much a metal will bend and how much force it will require to bend a particular amount. To look at any of the strength or deformation properties however temperature must be held constant. Since most rolling processes are conducted at a set temperature, often room temperature in cold rolling procedures, this is a warranted assumption. Once this is done a graph of the stressed properties of a particular metal or alloy can be studied.

The graph most useful is the common stress versus strain graph. From this graph the permanent and elastic deformation can be determined given an amount of stress. A line is drawn parallel to the elastic part of the stress versus strain graph from the point where the highest stress reached during the operation to the elongation axis. From zero elongation to where the sketched line intersects the elongation axis represents the amount of permanent elongation, this can be seen in Figure 6. Now another line is drawn parallel to the stress axis from the point of maximum stress to the elongation axis. From zero elongation to the point that the new line intersects the elongation axis represents the total elongation, the difference between the total elongation and the permanent is the elastic or the part that will return to its original length.

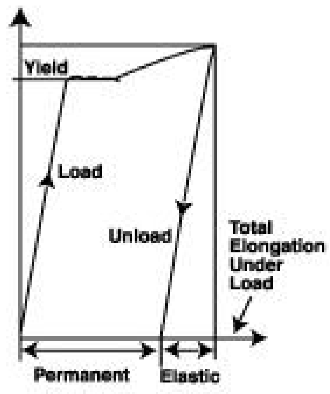

Figure 6: Graphical representation of permanent elongation [9]

This simple graphical representation helps to illustrate the relationship between the amount of stress and elongation. The elastic elongation will be proportional to the spring back of the material and the permanent is the amount of elongation that will not change when the metal is unloaded.

The stress versus strain graph may also be used to describe the range of formability that is desired in a process. For a forming process the stress must be greater than the yield strength, but less than the tensile strength, this range is highlighted in Figure 7. Any less than the yield strength and the material will not deform plastically and any greater and the metal will lose its formability.

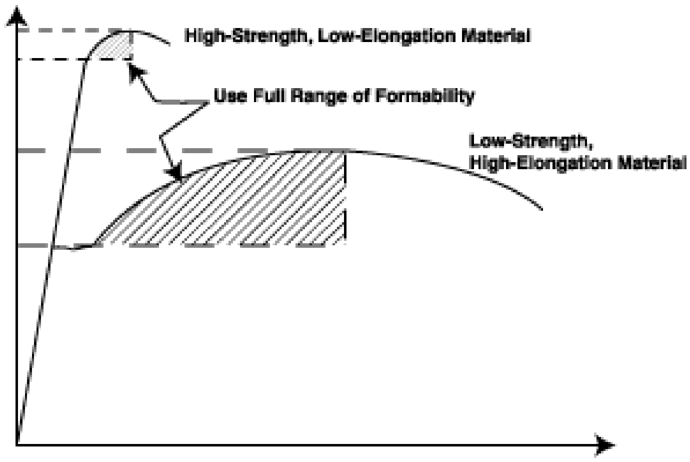

Figure 7: Range useful for formability [9]

With these considerations in mind one can now start to look at different materials in terms of the process. Materials with higher yield and tensile strengths generally have shorter ranges of plastic deformation. So a material like high carbon steel, which is significantly stronger than a typical mild steel will require more force to strain it a particular amount and will be able to be strained less before it reaches its tensile stress and becomes useless, this is shown graphically in Figure 7.

To select a material the properties discussed above must be understood, so that the selector my properly determine how they will affect the process. Aluminum for instance is often assumed to have fairly standard properties. It is often over looked as to what type of alloying has been done, if the sheet has been strain hardened or annealed, etc. All of the processes can greatly affect the properties of the material. Some types of Stainless Steel for instance are better suited for roll forming processes than others. The differences between roll forming a SS compared to a mild include more; springback, power required to form, and or better lubrication. Aluminum also requires good lubrication as well as well finished rollers to prevent in transference of roller imperfections on to the sheet being rolled.

5 Metallography Background

The basic assumption of metallography is the microscopic scale of a material determines how the metal will react macroscopically. A metallographer's hope is to understand how the microstructure affects the properties of a metal. The study of a material should include an understanding of factors effecting a certain operation, allowing the metallographer to design processes for materials. When a material is plastically strained, the microstructure must change in some way to allow the material to hold a deformed shape. Most materials used in manufacturing are not composed of a single crystal or a single repeated structure, but are polycrystalline. As Brick states in his 1984 metallography book: “It will readily be appreciated that deformation of a polycrystalline metal is an exceedingly complex process, one that has thus far withstood accurate scientific analysis,” [10]. While there has been some progress with more advanced techniques like SEM and TEM microscopy, the workings of a polycrystalline metal are still complex.

To understand what is happening when a polycrystalline metal is deformed it is useful to first understand the scope of a single crystal, and the mechanisms at work within one, because the reactions of a polycrystalline material will be the average of each single crystal’s reaction.

A single crystal is defined by the alignment of all its atoms in a specific repeated pattern. This pattern does not change within a single crystal by definition, but there are some inconsistencies in the pattern where the material may be shifted, called dislocations. A dislocation can be either the presence of an extra atom, or the absence of an atom, called a vacancy. Dislocations are the mechanism by which grains deform. A pictorial representation of one way a dislocation may propagate is given in Figure 8. It is understood that these dislocations may continue perpendicular into the paper for some amount of rows, thus a point dislocation could be seen as a straight line if the observer were to look at the “top” of this representation. As long as these dislocations remain relatively spread out the material is still considered as one crystal. If, however, many dislocations occur along an entire plane, a grain boundary is formed. A grain is a single crystal with one consistent lattice structure. Imagine that a grain is viewed from one side, where the planes of atoms appear as lines, and the lines lie parallel to one another, separated by an amount equal to the spacing between atoms on a line. Where two grains meet, a grain boundary is formed, as shown in Figure 9.

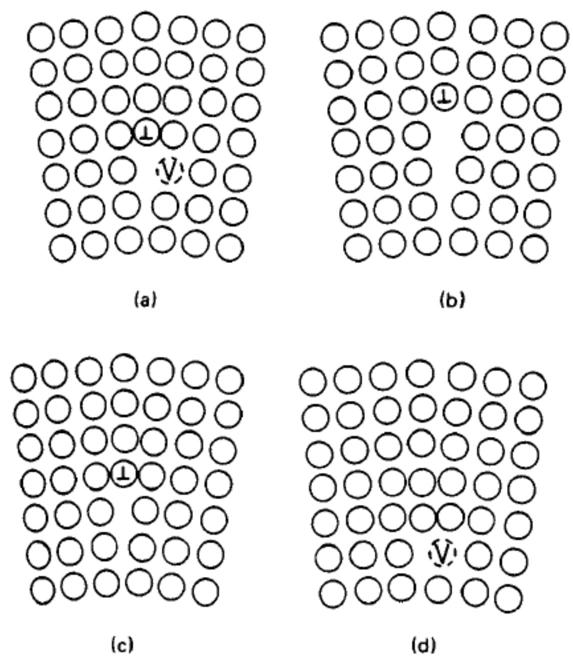

Figure 8: Dislocation propagation in a crystal lattice [11]

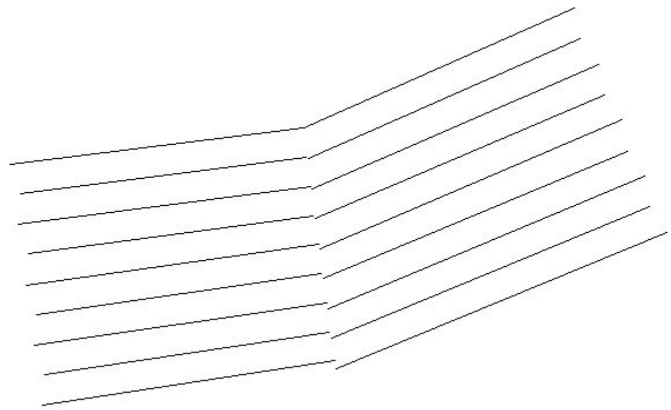

Figure 9: Grain boundary formation

A low angle grain boundary, less than 15 degrees in difference, can be viewed as a plane or set of planes of dislocations creating a separate grain. Figure 9 is a representation of a low angle grain boundary; the section where the two grains come together is an area of dislocations. Higher degree grain boundaries, 30-40 degrees, may be viewed as narrow regions of several atoms in thickness where grain arrangements change from one orientation to a different one [11]. Thinking of grain boundaries as an area where the arrangement of atoms changes from one orientation to another is simplest. Grain boundaries are heavily disordered regions; they are regions of high energy. Grain boundaries would like to be at lower energy levels, if possible.

As a material is worked, the amount of dislocations increases. In an unstressed crystal the amount of dislocations is often on the order of magnitude of 10^6, while a heavily worked material may exhibit 10^{12} dislocations [10]. Dislocations are the main hardening mechanism in the material because they interfere with the movement of other dislocations, restricting the range of elongation in the material. This is why materials become harder the more they are worked. In the same light it is often easier to move material inside a grain than it is to move a grain boundary.

Earlier in this section, it was stated that most materials used in manufacturing are polycrystalline materials. Understanding the behavior of these materials involves understanding how a single grain will react with its neighbors. The width of a dislocation is on the order of magnitude of 10^{-12} meters, the same magnitude as an atom. Even with the most powerful TEM microscopes, often only groupings of dislocations can be directly observed. Grains are typically on the order of magnitude of 10^{-6} meters, although they can be much larger. Comparing the size of a dislocation to the size of a grain is equivalent to comparing the size of an ant to the size of the Earth; a difference of six orders of magnitude. While dislocations are important to grain motion, they are often inferred and not observed. Grains are usually large enough to be observed directly with an optical microscope.

5.1 Tensile changes

Understanding the deformation of a single crystal in response to a tensile stress is useful in understanding the grain deformation of a polycrystalline material in response to tensile stress. The deformation of a polycrystalline material is the average of the behavior of all the differently oriented grains of a material [11]. It is well known from statics that the maximum shear stress in a material under tensile load occurs on a plane who's normal is angled 45^o from the tensile axis, as shown in Figure 10 when $\varphi = 45^o$. In a single crystal however, slip occurs along the slip plane of a material. There are three basic laws governing this slip. First, the direction of slip is always along the closest packed plane of atoms. Second, the slip usually occurs along the closest packed plane. Third, for a given set of slip systems, the direction and plane of slip, the slip occurs on the system where with resolved shear stress is the greatest. Figure 10 shows the slip plane where the resolved shear stress happened to be the greatest in this crystal.

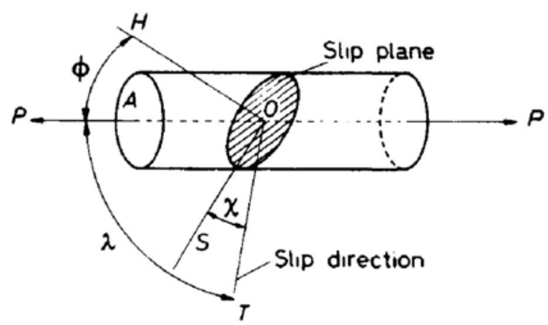

Figure 10: Slip plane with the maximum resolved shear stress [11].

BCC metals like room temperature steel are slightly more complex to than this simplistic model. Although there is a single close packed direction of <111> there are three other high density packed planes {112}, {110}, {123}. Iron often slips along all three planes at once along the same direction [11]. This creates a wavy line where a straight line normally occurs. Regardless of this interesting behavior iron will still slide along the same slip direction, causing the wafering shown in Figure 11b, as long as the ends are unrestrained.

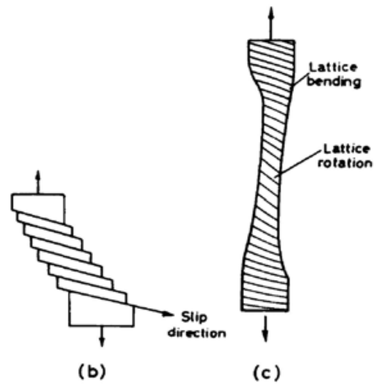

Figure 11: The wafering of a single grain [11]

Figure 11c shows a crystal's ends that are restrained during a tensile test. Since the ends cannot move laterally, the lattice must bend and rotate to accommodate stresses. In a polycrystalline material, grains are in constant contact with other grains and are restrained to a degree. When stresses reach the boundaries of grains that have the orientation best aligned for slip, stresses will propagate to neighboring grains [10]. Stress propagation in a polycrystalline material causes a push-and-pull motion between grains. The actions of a single grain are anisotropic and the choice of slip plane depends heavily of stress orientation. If grains are orientated randomly in a polycrystalline material, as they will often are, the material will behave isotropically [10].

5.2 The Properties of steel

Industry defines steel as an iron alloy having between 0.008 and 2.0 percent carbon by weight. At room temperature iron can only distribute 0.008wt% percent carbon within its matrix. This phase is often referred to as the alpha or ferrite phase at room temperature. Steel containing more than 0.008wt% carbon at room temperature will form a second phase referred to as pearlite or cementite. Near the eutectoid point on the iron-carbon phase diagram nearly 100wt% of the structure will be cementite at room temperature. The eutectoid point occurs at 0.6wt% carbon, therefore at room temperature between the 0.008 and 0.6wt% carbon the structure is a mix between ferrite and cementite.

Most manufacturing steels will be within 0.008 to 0.6wt% carbon and therefore will have a mixture of ferrite and cementite. The proportion of each phase in steel is based on the proportions of iron and carbon, as well as any processing. Processing includes initial casting of the material and hot working processes. For example, if the material was heated and then quenched, less carbon would precipitate out of the austenite phase, and the microstructure would look different than an unquenched material with the same composition.

For fully annealed steel heated to the annealing point and then cooled slowly enough for equilibrium conditions to set in, the phase diagram can be used to calculate the proportion of ferrite and cementite in the grain structure. Annealed steel is approximately 55wt% cementite and 45wt% ferrite. The ferrite phase is ductile and forms grains – portions of ferrite with a single crystal orientation. Ferrite grains will react similarly to the theoretical grains discussed earlier. The cementite phase is considered an aggregate instead of a grain, consisting of layers of carbon stacked on layers of iron. Such a stacked structure is called a laminar structure. The cementite phase is very hard and brittle, often breaking into smaller pieces under heavy cold working. Any analysis of the two-phase ferrite-cementite structure subject to cold working must take the behavior of the two phases into account

5.3 Theory of 2-D Optical Microscopy

The process of examining grain microstructures under an optical microscope has some basic limitations. Examination of the three dimensional structure in two dimensions requires extrapolation of the two dimensional data back into three dimensions. For instance, cross-sectional area of individual grains will change depending on the location of the section along a grain axis. Conclusions drawn about the three dimensional structure should not be based solely on the behavior of a few grain sections. In order to draw sound conclusions about even the two dimensional structure of a material many large samples need to be taken, as grain orientation within the microstructure is random. For example, in order to measure average grain size, several large samples should be taken and averaged.

5.3.1 The theory of sample preparation

Samples are cut into sections by a wire cutting machine; this is called sectioning. Often samples are very small or oddly shaped; mounting is needed otherwise it will add to the difficulty to following steps. Compression mounting with the material Bakelite is a popular and simple method. Prior to mounting, it is often necessary to clean samples. To minimize the potential for cracking samples with sharp corners should be beveled. To mount the samples, the specimen must be cut to a size that will fit inside the mold with adequate clearance. The surface to be polished is placed face down on the center of the ram surface. Clearance between sample and mold wall should be at least 1/8 inch. After the sample is oriented on the ram, the ram is lowered to the bottom of the mold. Then appropriate amount of Bakelite powder, at least ½ and inch higher than the sample, is poured into the mold. Heat and pressure are applied according to the requirements of the type of Bakelite used. Temperature control is more critical than pressure control, the temperature should be above 150 degrees Celsius, the will often be a pressure sensor on the machine that will indicate if more pressure is needed. Once the mold is properly cooked, cooling the specimen under pressure for about twice the cooking time is necessary so that the Bakelite will properly set. The operator should be careful when removing the specimen as the Bakelite often sticks to the side of the forming cylinder and has a tendency to suddenly pop up after several cranks. For this reason the cover on the machine is often kept on during freeing.

Sectioning of the sample should be done carefully if the cutting machine overheats the sample this might change the grain structure at the cutting edge and will be too time consuming to remove this damage with grinding [12]. To get the sample relatively free of distortions caused by cutting, grinding and polishing are used. The word relatively is used because grinding and polishing can only get the distortions to a depth that will not cause skewing of the view; this depth is between 10-100μm for hand grinding [12] and 1-6μm with polishing. The level of polishing depends on the level of magnification, but the most important goal is to make sure scratches and distortions will not be confused as features of the grain structure.

Typically finer and finer grades of emery paper or another type of abrasive are used to remove the distortions of the previous step. A commonly used progression is 120-, 240-, 400-, 600-grit abrasive paper. In between steps the sample should be rotated by 45-90 degrees to reduce additive scoring caused by adding to scratches in the same direction. Time spent at each step is usually recommended to be at least twice the amount of time it takes to remove distortions caused by the previous step, which for most metals is typically 1-2 minutes. In between grinding steps it is good practice to wash the specimen under running water to assure that and particles on the metal will not cause scoring at the next stage.

Wet grinding can produce better quality grinding as well as increase paper life. Smearing can be caused by the grinding media not contacting the part fully due to clogging of the media during dry grinding; wet grinding will remedy this problem. Clogging will also slow down the rate of metal removal. During preparation when a clogged paper was replaced metal removal rate increased substantially. Wet grinding will also help cool the sample, which reduces the chance of overheating the material and causing unwanted grain alterations.

Polishing the material will remove the abrasions that grinding cannot. Its purpose is to produce a flat, reasonably scratch-free surface with high reflectivity. Polishing often uses a floating abrasive in a solution; diamond particles are a common abrasive for polishing. The floating abrasive is added to a spinning cloth wheel. When polishing it is a good practice to move the sample from the center to the edge in a linear motion to prevent comet-tailing in the material. The aim of both operations is to produce a sample that is not significantly distorted, meaning that distortions caused by preparation will not be confused for grain features.

After polishing, the last step is to etch the sample, but testing the surface under the microscope first will allow the operator to make sure that there are no scratches on the surface of the material that might impair viewing. If there are not any obvious scratches, the sample can be etched otherwise the operator should go back to previous steps. A common etchant is 3~5% nitric acid in alcohol solution. The etching time depends on the material, but is generally less than 60 seconds for steel [12]. Of course the mass fraction of nitric acid can contribute to the etching time and final result effectively. Under-etching fails to reveal all the details while over-etching obscures details. Etching is a controlled corrosion process. Material at the grain boundaries will corrode much more quickly than the material in the grains. This causes a pit at the grain boundaries. Normally grain boundaries are only several atoms thick, this process will make the grain boundaries appear much thicker. The thickness of the grain boundaries and thus the apparent size of the grains can be heavily controlled by the strength of etchant and etching time. For this reason it is often a good idea to use an etchant solution that requires more than 20 seconds to get the "proper" etch. This will allow the etch time to be more easily standardized. If the etch time is shorter than this a small change in etch time like a second will have too great an effect on the apparent grain structure.

6 Investigation and Analysis

6.1 The Company Predicament

Designing this project was often a mix of understanding, which techniques might allow the group to best analyze the process and what methods were available to the group. After careful study of the variables in tooling design and system stability it was made clear that the method for understanding stresses within the material must be optical light microscopy. The equipment had been purchased ahead of time because of the serious time constraints of the project and was the group's only option. Initially using strain gages to understand stresses in the roll forming material was of interest, this interest had to be dropped because of constraints on equipment and time.

6.2 Duplex Grain Structure Analysis

Initially, the profile sections appeared to have a duplex grain structure possibly composed of pearlite aggregate and ferrite grains. A duplex grain structure, as described by Voort, has a bimodal frequency distribution of grain sizes [12]. According to initial hypotheses, pearlite aggregate would fracture into smaller pieces under plastic deformation of the work piece. If some of the grains were fracturing, then a basic assumption - that shrinkage of a grain section indicated elongation - would be baseless.

To determine whether a duplex grain structure existed and was detectable, a variation of the Heyn method analysis was run. The method, proposed by Underwood, entails drawing randomly placed lines over a metallograph and measuring the linear intercept length of each grain on the line. A frequency distribution is generated by tallying the number of grains that fall within specific intercept length intervals. No bimodality was revealed after analyzing several samples. Therefore, even though pearlite grains may be present, the linear intercept method as implemented in this project could not differentiate between pearlite and ferrite grains. Furthermore, the procedure was immensely time-consuming and would not permit a thorough analysis of many samples.

The suspicion that fracturing pearlite aggregate would render the standard Heyn method ineffective was based on only a basic understanding of the etching process and metal composition. It is possible that pearlite aggregate is present, but is indistinguishable from regular grain boundaries after etching. Etching reveals grain boundaries because the etching agent reacts more readily with the higher-energy grain boundaries than with ordered, crystalline grains. Pearlite aggregate may also react more readily than crystalline grains, appearing very similar to grain boundaries under a light microscope.

6.3 Heyn's Method Analysis

6.3.1 Heyn's Method Background

An appropriate method to analyze the attributes in question should be determined. Many methods for grain analysis have been developed by metallographers since the inception of metallography. If the grain size and shape are of interest to the analysis a useful measurement would be the average cross-sectional dimensions of the grains. If a line is drawn across a grain the distance that intercepts the grain is referred to as the intercept length. In a grain structure which may consists of hundreds of grains per field it is not an effective use of time to analyze the dimension of each grain. Instead many randomly parallel lines are laid on a grain picture to analyze the structure in one direction. If the number of grains along a line are counted and the line length is known than the length of the line can be divided by the number of intercepts. This quantity will be the average length of the grain at this particular magnification. This is called mean linear intercept method (Heyn's method) and the most popular method for analyzing unimodal structures.

The mean linear intercept length is the average length of a line segment that crosses a sufficiently large number of grains. It is determined by laying a number of randomly placed test lines on the image and counting the number of times that grain boundaries are intercepted. Mean linear intercept length is defined mathematically in Figure 12.

$$\bar{L}_L = \frac{1}{\bar{N}_L} = \frac{L_T}{PM}$$

Figure 12: Equation for linear intercept length [13].

Where N_L is the number of intercepts per total length of the test lines L_T, P is the total number of grain boundary intersections and M is the magnification.

When choosing a line length a length should be chosen that allows for 50-150 grains to be counted on each line. This will insure the method is accurate, choosing a line length that contains less than 50 is not accurate enough while more than 150 may be to cumbersome to count. It is a good idea to pick the magnification so that a line can be drawn across the majority of the field, so choosing the correct magnification should be done simultaneously with choosing the line length. It is also good practice to use at least five parallel test lines per field so that an average grain length in each direction of interest can be calculated. Remember that one line will produce one average length thus the average of five lines can be taken for the average length in a field of view. The previous step will add statistical confidence to the analysis procedure. If the shape and area of a grain are of interest, then multiple directions must be measured. A common set of directions are 0, 45, 90, and 135 degrees. This allows for an accurate shape of a grain to be calculated. With this set of angles a skeleton of a grain can be drawn by placing the average grain lengths about a center point like the diameters of the grain in each direction.

When choosing the proper amount of fields more than one field of the same structure should be chosen at random to insure that the data obtained in one field is accurate. Generally three to five fields are selected for each type of structure to be analyzed. To insure random selection of fields various techniques are often used. If possible the operator should not observed the field of view until a selection is set, this works well if there is a relatively large field to select from. In cases where there are very few homogeneous zones the best representative of the zone of interest should be chosen. In a section of material that has a large variability in stress concentration like a bend of a thin metal work piece stress level may change from one grain to the next along the radius of the bend. This means that any field selected in the corner will have a large variation in deformation; this should be accounted for in the analysis.

When counting the amount of intercepts, either counting the number of boundary intersections or the number of grain intersections can be used. When counting the amount of grains in a material each grain on the line should be counted as one. If the end of a line is within a grain, meaning it does not fall on a grain boundary then this should be counted as one half.

6.3.2 Analysis Procedure

The full step-by-step procedure used in this project is presented in the appendix, section 9.4.2. The counting method is identical to that suggested above. Grain images were imported into AutoCAD, and then five lines of equal length were superimposed over the image. The image was copied four times, providing one field of view for each analysis angle (0, 45, 90, and 135 degrees from horizontal). Intersection counts were recorded for each line in the program Heyn's Method 2.02 by Mike Meier, which then calculated the mean linear grain size, standard deviation, and other statistical data. Output from that program was manually imported into Excel for grain area calculation and for ready comparison with other samples.

6.4 Calculation of Grain Area

Average grain area combines the data from grain analysis in four directions into one easily grasped number. This section explains the procedure and equations for calculating average grain area from linear intercept data. Only simple geometry is used.

Linear intercept data presents average grain lengths in four directions: 0, 45, 90, and 135 degrees. This data is used to draw the skeleton of an average grain, as shown in Figure 13. The values L0 – L135 are half of their respective linear intercept length.

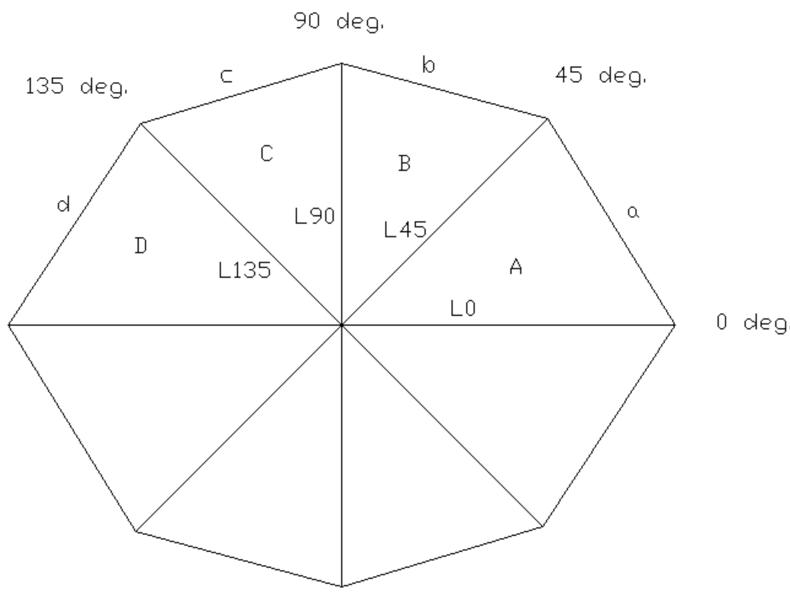

Figure 13: Geometry of an average grain. Length dimensions are entered from linear intercept data.

Calculating the total grain area is a matter of doubling the sum of the areas of triangles A, B, C, and D. Triangle areas are calculated using Heron's formula, as shown in Figure 14.

$$a = \sqrt{L0^2 + L45^2}$$

$$s = \frac{1}{2}(a + L0 + L45)$$

$$A = \sqrt{s \cdot (s - a)(s - L0)(s - L45)}$$

Figure 14: Heron's formula. Variables correspond to triangle A in Figure 13.

Excel was used in this project to quickly and easily calculate grain area for every analysis point.

6.5 Experiments

Only two real experiments were performed during the course of this project. The vast majority of working time was spent learning and refining the process required for producing acceptable sample images. Chronologically, the first experiment was an analyst variation experiment and the second was the tensile test experiment.

6.5.1 Analyst Variation Experiment

Introduction

The analyst variation experiment was designed after the results for the roll forming sample analysis were put together. The results indicated large grain size changes that made little sense, and strongly hinted at variation in analysis results between analysts. Initially, the purpose of the experiment was to generate some statistical data for variation between analysts in the hope that it could be used to filter the results of the roll forming sample analysis. As was with the case for many other aspects of the project, the experiment was started with only that hope and the statistical validity was investigated concurrently. It turned out there was no way to salvage the roll forming sample results by using statistical information from the analyst variation experiment. The experiment still has some validity, however, because it proves there is significant variation between analysts, and may indicate that the preparation procedure still needs a great deal of refining. Our feeling is that inconsistent results between analysts stems from unclear metallographs; the grain definition in most images requires the analyst to make judgment calls about whether the Heyn method line crosses an actual grain, and if larger grains exist as one or as a clump of smaller grains.

Purpose

Determine the variation in grain analysis results between analysts.

Equipment & Materials

- AutoCAD software by Autodesk
- Heyn's Method 2.02 software by Mike Meier
- Excel software by Microsoft
- One metallograph

Setup & Procedure

The metallograph was set up for analysis in AutoCAD according to the procedure in section 6.3.2 Analysis Procedure. Once the lines were drawn for each orientation, all group members performed counts on the same image and recorded the data using Heyn's Method 2.02 software. The data was further analyzed in Excel using the built-in ANOVA data analysis tool. A single factor test was run according to the analyst; each analyst was a treatment. Additionally, grain size was calculated from the results of each analyst for easy comparison with the results of other experiments.

Results

The P-value for all ANOVA results was very small, on the order of 10^{-7}, which means there is a very high probability treatments are responsible for variation of the means, according to Weisstein [14]. The average grain sizes for each analyst are shown in Figure 15. The size range was 32 μm^2, or 46% of the maximum average grain size. For comparison, the variation between average grain sizes in the tensile test results was $13 \mu m^2$, or 12% of the maximum. There is too much variation between different analysts right now to compare the average grain sizes between roll forming stages.

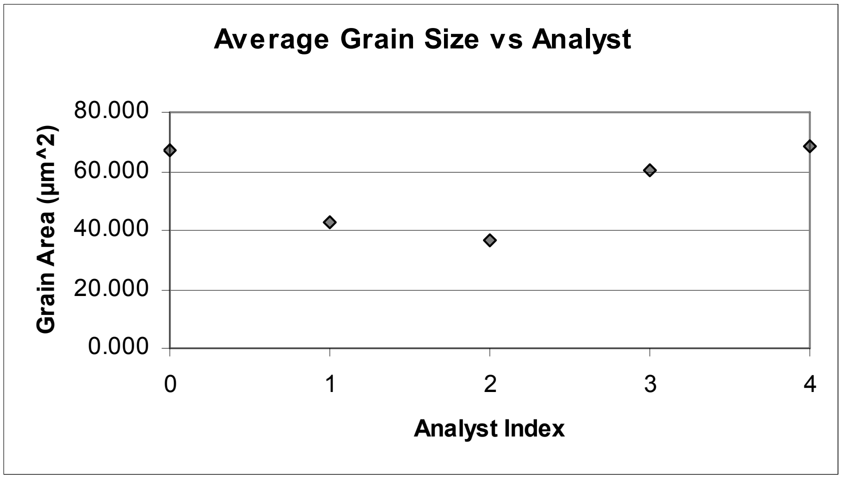

Figure 15: Average grain size vs. analyst. There is very large variation in average grain size between analysts.

6.5.2 Tensile Test Experiment

Introduction

The tensile test experiment represents the final achievement of this project. Its purpose was to link a known tensile stress to grain deformation in the microstructure. Once a relationship between a known stress and grain deformation was established, the results of the roll forming line sample analysis could be interpreted, and conclusions could be drawn about the existence of tensile stress components in the work piece. Any tensile stresses large enough to cause plastic deformation in the work piece are redundant stresses because they do not contribute to forming the work piece profile. This is only one small part of understanding the stress distribution in the whole work piece.

Purpose

Link grain distortion with work piece stress.

Equipment & Materials

- Prepared tensile test specimens (fully annealed 1045 steel)
- Tensile test machine
- Metallograph sample preparation equipment
- Imaging equipment (metallography equipment, camera, etc.)
- AutoCAD software by Autodesk
- Heyn's Method 2.02 software by Mike Meier
- Excel software by Microsoft

Setup & Procedure

In preparation for running tensile tests, many specimens were stamped from fully annealed 1045 strip stock – the same as used on the roll forming line. Five specimens were tested to failure to establish the ultimate tensile strength and yield strength of the material. The range between YS and UTS was divided into quarters to determine the stress levels for subsequent tests. See Figure 16 for clarification.

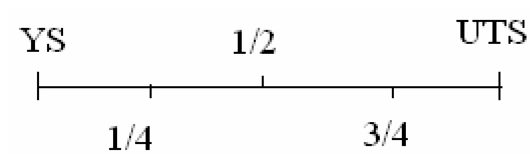

Figure 16: Determining testing stresses in the plastic deformation range.

Three specimens were then stressed to 25%, 50%, and 75% of the plastic range. Sections were taken from the same location in each sample for metallographic analysis. Sectioned samples were prepared and analyzed according to the procedure summarized in

6.3.2 Analysis Procedure. One person analyzed all tensile specimens to eliminate variation between analysts.

Results

The data suggests that tensile stress and grain deformation are related, specifically that average grain area decreases with increasing tensile stress. An error analysis was attempted, but ultimately abandoned for lack of time. Detectable grain shrinkage did not appear until around 75% of the plastic range, as seen in Figure 17. Each pair of points represents the average grain area of samples taken from different specimens stressed to the same level. The ultimate tensile strength appears around 474 MPa, 75% range around 451 MPa, 50% range around 425 MPa, and 25% range around 408 MPa. As can be seen from Figure 17, there is no detectable grain area shrinkage below 50% of the plastic range. This brings the suitability of examining the grain structure for work piece stresses into question.

Just to check that the grain shrinkage apparent in the grain area graph was not the result of error propagation through the calculations, an average linear grain size graph was also prepared. This graph, shown in Figure 18, supports the analysis results shown in the average grain area graph. The average linear intercept length still decreases around 75% of the plastic range.

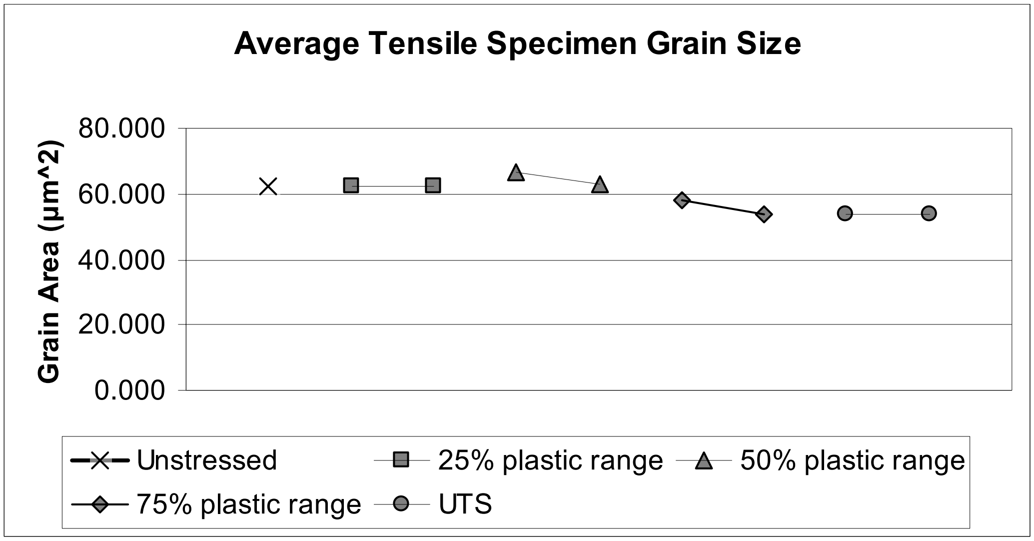

Figure 17: Average tensile specimen grain size. The average grain size changes suddenly around 75% of the plastic range.

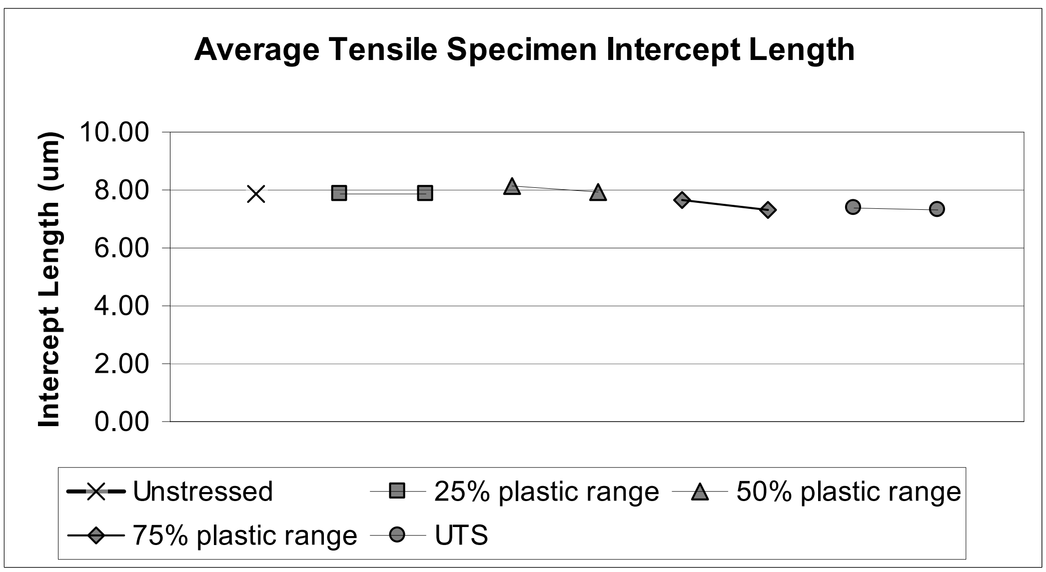

Figure 18: Average tensile specimen linear intercept length. The average intercept length still changes around 75% of the plastic range, though it is not as dramatic.

7 Conclusions

7.1 Experimental Results

The two experiments in question are the roll forming line and tensile test. Each was a preliminary experiment and both require a larger body of evidence to be validated. This is mostly due to time constraints and as such the experiments lack reproduction. This does not mean that these preliminary experiments cannot be evaluated. The limited quantity of experiments should be kept in mind when evaluating the validity of this approach.

The purpose of the roll forming test is to correlate stress distribution and severity to micro structural changes. There were two objectives: first, measure and quantify the severity of forming in the bends at each pass. Second, locate stresses in areas they should not belong, thus locating redundant deformations. The second aspect depends on the tensile test, which should prove or disprove the feasibility of locating redundant deformation. Preliminary results from the roll forming line test show that grain distortion can be measured and visualized.

It was hoped that calculating grain distortion would lead to a grain distortion gradient that could be superimposed over the part cross section. The gradient could be useful for understanding the stress distribution in the cross section. The distortion could be quantified by calculating a ratio between the longest and shortest dimensions of an average grain. In this case, it will be important to keep the sample orientation consistent so that distortion ratios can be accurately located on the profile. Also, in future experiments mis-orientation could lead to a misinterpretation of any visual data. If one sample is rotated 5 degrees with respect to another and the sample should have the same grain shape it will appear that the samples are 5 degrees different. This variable was not watched closely, although a conscious effort was made to orient the samples similarly.

The main problem with the results was the variation between analysts. Since the variation appears to be 3 times as large as the as the variation between forming stagers, a quantitative analysis of this data is impossible. The variation between analysts should be much smaller than the difference between roll forming stages.

The tensile test did not suffer the fate of roll forming test, instead one analyst was used to rule out any variation between analysts. This does not rule out any changes conscious or unconscious in the tester's counting. It is believed that the variation is largely due to the subjectivity of what constitutes a grain. This will be discussed later in the section.

The tensile test experiments show that distortion is only detectable deep into the plastic range and grain area shrinkage is not linear. No noticeable change in grain area occurs until approximately 75 percent of the tensile range. For any method of measuring plastic stress to be useful, it must be able to detect shrinkage immediately upon entering the plastic range.

It is believed that that any variability in the counting of grains is due to the poor quality of the pictures used. The quality of the pictures needs to be increased enough so that when a variation between analysts experiment is carried out the variation is significantly smaller than bend to bend changes. A low variation would indicate a small amount of subjectivity and thus improve any variation in a single tester's own counting.

7.2 Recommendations

7.2.1 For Future Experiments

As alluded to in the previous section the main concern for variability in grain size was the clarity of the grain pictures. The group does not believe that the metallographic approach should simply be abandoned based on a poor initial showing. The sample preparation procedure, namely the etching situation needs to be revised. It is believed that the grinding and polishing methods produce a relatively distortion free surface. The variation seems to be introduced during the etching phase. First as stated in the metallurgical background 1045 steel contains a duplex grain structure, the etching method should be able to produce a sample, which can be evaluated clearly. A murky not thick grain boundary should not be able to be confused with an agglomeration of pearlite. With the current pictures it is often impossible to discern the difference. Also etch time need to be carefully controlled, grain boundaries will appear thicker after longer etching time and thus skew features.

This project never solved the problem of where to look for redundant deformations. This could be accomplished using an optical comparator, which CIS currently owns. The actual dimensions of a finished profile could be measured and compared to the theoretical dimensions. If certain dimensions are consistently different this might indicate a place to look for redundant deformations. If dimensions are consistently different than the theoretical it is likely that the cause is something consistent. For instance excessive unplanned for tensile stress causes a section to elongate thus the measurement is consistently longer than the theoretical value.

If future analysis shows that the metallographic approach does not provide adequate results, then other methods will be needed. The feasibility of the methods has not been investigated some initial thinking was done. Placing strain gages directly onto the part would allow for direct measurement of the strain, which could then be correlated to stress by using a similar tensile test experiment. The strain gages are used to record strain during the test. Strain gages can be highly accurate. This method would be much more direct and looks to provide results more quickly.

7.2.2 For Future Teams

This section is here to help future groups of students and advisors work more effectively. It is not a meant to judge any of the help we were given and are thankful for. There are always improvements, which could be made and this section will shed light upon some important ones. The project was often riddled with delays and unforeseen hang-ups. Many of these could have been reduced or eliminated if the following were implemented.

The project feasibility should be determined as soon as possible. Advisors and students should have a solid idea of what the seven weeks in China are going to entail. This should only be done after all parties are familiar with the process of roll forming. During the planning stages students often do not know or have any way of telling how long testing should take for instance. Having an advisor that has experience with the particular subject matter would help with more accurate estimates. Communication is essential - whether it is between the students and advisors, the students and themselves, or the advisors and themselves. Start communication as early as possible and as often as possible.

7.3 Personal Interpretations

7.3.1 Doucet

This project to a severe turn soon after our first visit to the company, it appeared that most of the background completed before then would not deal with the project. In the end it was very useful to have a good basic knowledge of roll forming and quality control. More focus on topics used in the actual project work, namely metallography, would have allowed for more productive experimentation. At the same time it was useful to wait until the project group obtained good background knowledge before being lead in any particular direction.

Finding the effects of stress in the microstructure of a material is a logical application of metallography. As hinted to in the metallography background section of this report the interactions within a polycrystalline material are very complicated. To further complicate things, stress first effects the material on a much smaller level than was studied in this project. Using the ant and Earth analogy, changes on the scale of ant must move enough to be measured on something at the Earth's scale. It is still unclear to the group how much stress is required before noticeable changes in grain structure become detectable. A possible value was found at 75 percent the elastic range, but this experiment should be repeated with higher quality sample pictures. The important value here is the threshold of stress measurement, if is not close to the yield strength this method is useless.

7.3.2 Jorgenson

I feel the concept of microstructure analysis to detect stresses within a roll forming work piece has not yet been proved invalid. We did not get consistent analysis results between analysts, but this may be due to imperfect sample preparation. Though we performed no experiments to prove it, I feel the source of variation between analysts stems from poorly resolved metallographs. Logically, a very well defined microstructure should not require any subjective judgment calls by an analyst, because grain boundaries would be clear and indisputable.

The validity of microstructure analysis as a tool for detecting work piece stresses should not be denied until consistent analysis results have been realized. It may turn out that microstructure analysis does not have the precision required for stress analysis. For example: if future tensile test experiments support the data obtained in our first tensile test experiment, I would conclude that microstructure analysis is useless for detecting redundant stresses in a roll forming work piece. The stress magnitude where grain size change becomes detectable is just too far into the plastic deformation range. Stress should be detectable as soon as it surpasses the yield point of the material, especially when looking for redundant deformations – permanent deformations that do not contribute to forming the part profile.

The results of our tensile test analysis are suspicious. They reveal only one change in the average grain area at around 75% of the plastic range. Intuitively, I would anticipate a more continuous shrinkage of average grain area, though intuition has little meaning when dealing with scales well outside the human realm. The nature of the Heyn method may be somehow responsible for the single-step pattern observed in the analysis results. It takes the first average of grain sizes when the line is drawn. Subsequent lines, or samples, are then again averaged to generate a mean of means and associated statistical information. This would seem to be a robust and error-tolerant method suitable for microstructure analysis. However, the grain sizes in our samples may be too variable to get useful results from this method. A duplex grain structure analysis was initially considered because our research indicated that annealed 1045 carbon steel should have two distinct phases that behave differently when cold-worked: pearlite aggregate and ferrite grains. In order for our analysis method to ever be of any use, the continuous shrinkage in cross sectional area of ferrite grains should be proved.

We had the opportunity to talk with a doctoral candidate at Tsinghua University in Beijing who was also doing microstructure analysis work. His first reaction to using the Heyn method to analyze the grain structure was that it took too much time. The only reason to use the Heyn method to determine average grain size is to detect grain distortion as well. The Heyn method was chosen because we originally wanted to generate a “grain distortion gradient” that could be superimposed over the part profile. We suspected a distortion gradient would be useful for further understanding the stresses and behavior of the bent part. If the distortion of grains is of little interest, than there are other, faster methods in use – particularly methods that can be automated.

I am proud of our group and the project. We were put in a difficult situation where no group members had previous knowledge or experience with the subject matter. In the span of a few days we managed to break the problem down and, through research, teach ourselves enough about the subjects to form decent hypotheses. By saturating ourselves in the problem and the research, we were able to design and run an experiment, and identify areas for more investigation in the future. Specifically for Jake and me this project was a test of our WPI education, which has trained us to learn quickly and effectively find the information we need. Finding focus for the project was also difficult, as the problem was large, ugly and unwieldy. I think our success in digesting the volumes of information on so many subjects in a timely manner, and then applying the new knowledge in a useful way is something to be proud of.

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9 Appendices

9.1 System Stability Breakdown

With points that will effect machine consistency and performance. This is a general list that was put together from a few roll forming texts.

- **Roll Formers** (structure on which tooling or "form rollers" are mounted)

  Consistent, repeatable setup is important. Factors affecting consistent setup:

  - Roll former alignment
    - Top and bottom roller shoulders coplanar
    - Bottom roller shoulders coplanar
    - Top and bottom rollers parallel
    - Check over the setup procedures used by CIS. Maybe they can be streamlined or fool-proofed in some way to make the setup more consistent?
  - Drive train condition
    - Gearbox in good condition
      - Proper lubrication
    - Roll former drive gears in good condition
      - Proper lubrication
    - See what kind of maintenance practices CIS uses. Worn equipment could cause some problems, though probably not very important for reducing normal process variation.

- Structure condition
    - Roll former bearings in good condition
        - Proper lubrication
        - No play or excessively worn bearings
    - Bearing block sliders in good condition
        - No play. Play will affect roller shoulder alignment
    - Adjustment screws in good condition
        - No stripping, no play. Will affect precision of top roller adjustment.
    - Vertical alignment system in good condition
        - No play or backlash. Will affect precision of top roller adjustment
        - Use strong springs to eliminate backlash
    - Again checking the wear condition of the machine. Bearings and bearing blocks might cause some unnecessary variation if they are not in good condition or if loose and unaccounted for during the setup process.

- **Lubrication System**
    - Recirculated lube maintained
        - Clean storage tanks. Effective filters and cleaning processes
    - Lubrication appropriate for process
        - Evaporative, synthetic chemical solution, semi-synthetic micro-emulsion, soluble macro emulsions, petroleum based

    - Adequate lubrication of form rollers and stock
    - Lubrication may not contribute as much to process variation as material variation, but it is important for tool life and product surface quality. Running without lubrication or coolant could cause some problems.
- **Form Rollers** (roll form tooling)
    - Form rollers machined and designed correctly
        - Consistent relationship between material gap and shoulder gap (to make setting up the roll forming line easier and more accurate)
        - Profile interference check
        - Material gap is consistent throughout the profile
    - Material gap setup
        - Gap is consistent throughout setup without load
        - Form rollers gapped correctly under load
            - Test with the first run of material
    - We suspect reducing material gap variation, and matching it more accurately to the variation in strip stock is the best place to reduce normal process variation. Also, checking that the tooling is made correctly in the first place is obviously important.
- **Strip Stock Straightener** (to remove coil-set in strip stock)
- **Entry Guide**
- **Part Straightener**

- **Cutoff Die**
- **Drive train**
- **Stock Material**

Sources: Alvarez [6] and Nickel [7]

9.2 Quality Control Background

9.2.1 Process Capability (Cpk)

The precursor to process capability or Cpk was the process capability index or Cp. The process capability index Cp is defined as the ratio of the specification width to the manufacturing capability:

Cp = (Spec. Width) / (Mfg Capability) (Drake)

Cp is also thought of as a concurrent engineering index, because design engineers are responsible for setting the specification width, and manufacturing engineers are responsible for setting the manufacturing capability. Process capability had been historically defined as +- 3 Sigma, until the early ‘80s when it was redefined as Cp = 1.33, or +- 4 Sigma, as shown in Figure 19. The limits USL and LSL refer to the Upper and Lower Specification Limits, respectively.

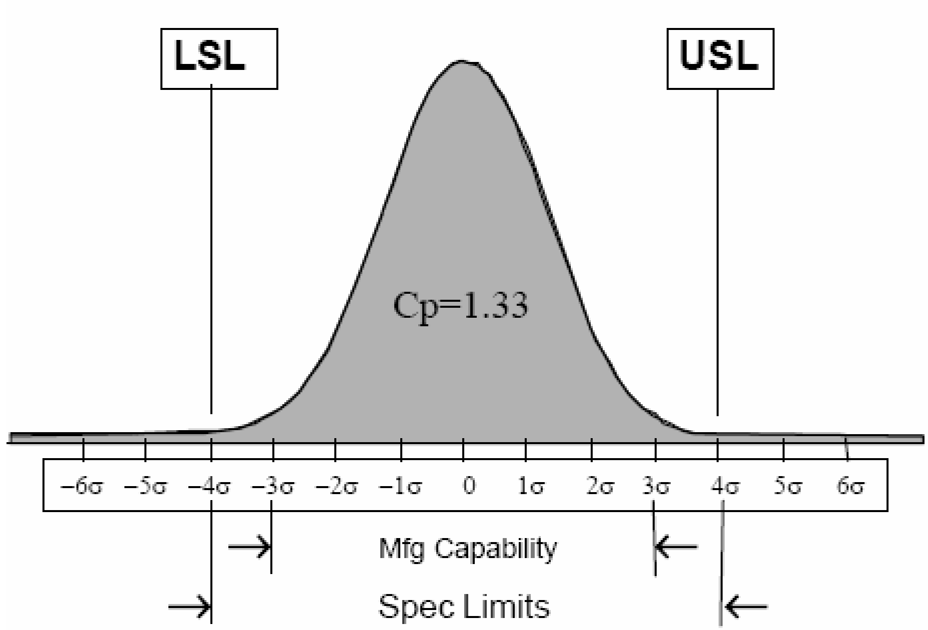

Figure 19: Normal distribution showing manufacturing capability and specification width [15].

The process capability index Cp did not take into account statistical shifts during long term manufacturing runs, so a new index called Cpk was created. Process capability, or Cpk, is defined as:

Cpk = Cp*(1 – k), where k = (shifted mean) / (distance to nearest spec limit)

The definition of Cpk is illustrated in Figure 20.

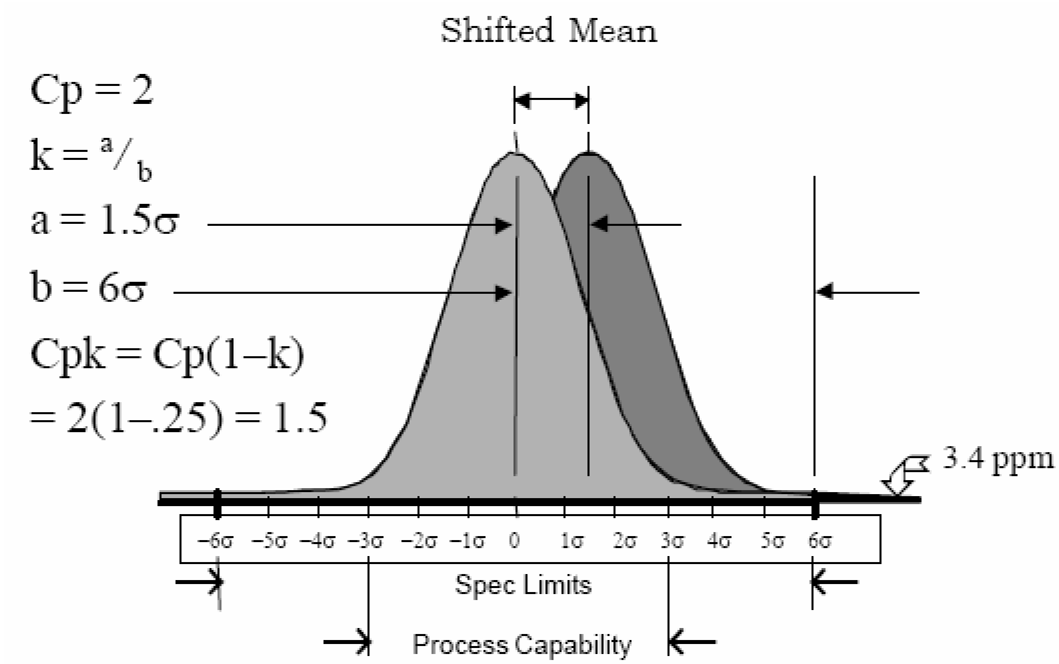

Figure 20: Normal distribution with shift incurred over long-term manufacturing run, and a definition of Cpk [15].

In the case illustrated in Figure 20, the design engineers set the specification limits at +- 6 sigma, yielding a Cpk of 1.5, or a Cp of 2. The process capability Cpk is a more realistic measure of capability because it takes into account statistical manufacturing variation.

9.2.2 Statistical Process Control (SPC)

To assure a quality product it is necessary to understand why parts are not being produced within the desired specifications. One such method for monitoring and determining problems in a process is Statistical Process Control. This system uses a normal Gaussian distribution to determine the range of acceptable product distribution. Any normal process will have a distribution shaped like the Gaussian bell curve in Figure 22 where the majority of the products produced will concentrate towards the middle of the curve. Figure 22 shows a normal Gaussian distribution, in a process; the y-axis represents the frequency of the measurement in question, and the x-axis represents the measurement in question. If one were to impose a range of excepted measurement values the wider the range the larger number of parts would be contained within the range. There is a standard method for determining this range, there is a set length called a standard deviation that act as the units for the range. A standard deviation is the average amount of deviation from the average. The equation for determining the standard deviation of a distribution is shown in Figure 21.

$$\sigma = \frac{\sqrt{(x_1 - \overline{x})^2 + (x_2 - \overline{x})^2 + ... + (x_n - \overline{x})^2}}{n - 1}$$

Figure 21: Equation for determining the standard deviation of a distribution.

In the equation x is the value of a given sample, the $\overline{x}$ represents the average out of a given sample group and n represents the number of samples taken. Since a normal Gaussian distribution gives a standard curve there is thus a specific value for a standard deviation. To give an idea of what a standard deviation translates to on a curve consider Figure 6. Each color represents one standard deviation.

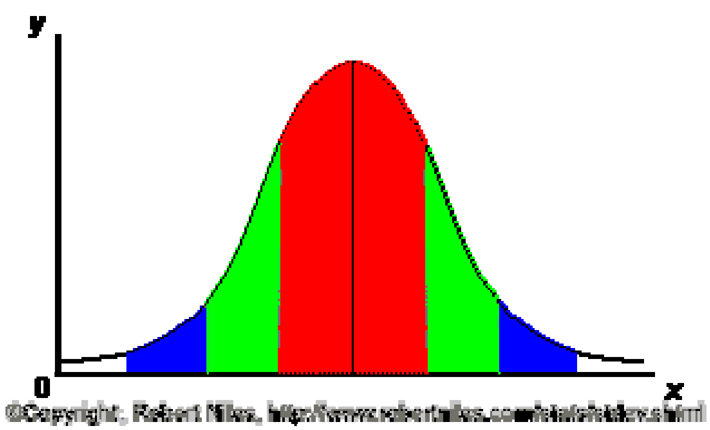

Figure 22: Standard deviation description [16]

Most often the industry standard is to take three standard deviations plus or minus the mean value or in other words the outside of each blue section as the upper and lower limits. These limits represent 99 percent of the measurements. The goal of any process is to get these statistical limits within the desired part limits. If this is true that means for ever 100 parts produced by a production line 1 of the parts will not be within production specifications. If a process on average stays within its statistical limits it is said to be "in control".

It was stated that a process must stay within the limits, yet the sentence before it was stated that 1 out of every 100 parts will not be within the limits. To adjust for these discrepancies a sample group is selected, usually between 2-10 parts, and then averaged and this represents one point in a graph. The upper and lower control limits are based on the addition and subtraction of three sigma from the mean. The mean in the case where sample groups are taken is the average of the groups, which is often represent as x double bar.

When a problem occurs in the process some type of drift will occur and the distribution will no longer be normal or may have shifted all together. When the process shifts the $\overline{x}$ terms will start to move towards the limits in some fashion. Based on prior knowledge many of the causes for such shifts can be quickly determined. If a tool is wearing the process will shift steadily with time, this can be seen in Figure 23a. Once the tool is replaced the process returns to normal. If the process is hovering around one of the control limits and not the mean it is possible that there is a tool setting that is not correct, this is often called a shift in the mean and can be seen in Figure 23b [3]. A quick shift in the mean can also indicate that a property in the incoming material has changed, which is shown in Figure 23c. This ability is the largest benefit of implementing a system like this, it quickly allows a skilled operator to determine problem and thus quickly get the process back within the desired range.

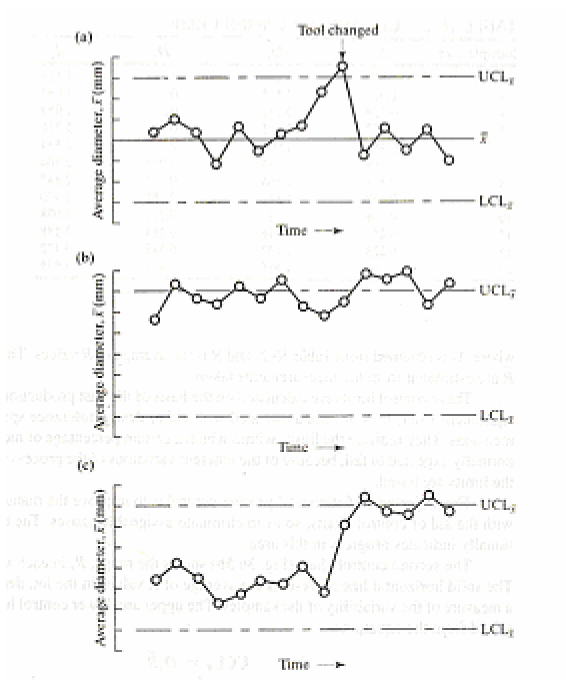

Figure 23: Examples of “out of control” processes [3].

The object of this system is to get the distribution of parts being manufactured within the required specifications. The distribution represents the statistical distribution of parts being manufactured the limits mark the edge of its range. The limits do not correspond to the actual measurement specifications, which are set by the designer of the part.

9.3 Sample Preparation Procedure

9.3.1 Step-by-step Sample Preparation Procedure

1. Section sample from roll forming line or other source.
    a. Cut to length with wire cutting machine *(Wire EDM??)*
        i. 1-2cm length
2. Mount section in Bakelite, if to small to be safely ground alone.
    a. Remove top metal cylinder in Weiyi XQ-2B molding machine.
    b. Place sample in molding machine.
    c. Turn on machine by turning timer to the “ON” position, for warming up.
    d. Cover sample with Bakelite powder without knocking samples over.
    e. Place top metal cylinder back in machine.
    f. Turn crank to pressurize the Bakelite until the yellow light comes on.
    g. Cook 8 minutes at a temperature between 135C and 150C. Make sure the yellow light remains on, indicating proper pressure.
    h. Turn machine off and allow to sit for 15 minutes to cool
    i. Remove sample.
3. Grind samples
    a. Wet grind. Each stage up to 1000# should take no more than a minute or two. The 240# stage should take less than 30 seconds.
        i. Drip or thinly stream water constantly onto the center of the grinding wheel. There is too much water when the sample begins to hydroplane and not enough when the Bakelite clogs the grinding wheel. Use moderate even pressure to achieve a flat grind.

ii. The goal of wet grinding is to remove loose abrasive and abraded material from the wheel so the sample isn't damaged. Wet grinding cools the sample, which is important when imaging grain structures.

iii. When grinding, the sample should be held in on orientation. Some oscillation perpendicular to the grinding direction is acceptable, but not necessary.

iv. When moving onto the next grit stage, wash the samples before using a finer grit to prevent contamination.

v. When moving onto the next grit stage, the sample should be turned 45^0-90^0 and ground until scratches left by the previous stage are no longer visible. Turn the sample another 45^0-90^0 and grind until those scratches are no longer visible. The sample is now ready to move to the next stage.

b. Grind with 240# until the sample surface is completely exposed and the edges are crisp.

c. Grind with 400#, following the procedure in 3.iii - 3.v.

d. Grind with 600#, following the same procedure.

e. Grind with 1000#, following the same procedure.

f. If storing the samples overnight, drop alcohol on the surface to remove absorbed water and prevent the surface from oxidizing over night.

4. Polish samples

a. Polish with metallographic specimen polisher.

i. Spray "diamond spray" polishing compound onto red polishing cloth.

ii. Pour enough water onto the cloth to keep it damp. A thin, evaporating film of water on the sample surface indicates good wetting. Water keeps the specimen cool and retains the diamond polish in the cloth as an abrasive slurry.

iii. Polish until all scratches from the 1000# grind have disappeared. Use light to moderate pressure to expedite the task.

iv. Polishing takes a while. Expect 15-30 minutes per sample. More time indicates a less-than-ideal polishing technique. Adequate wetting of the polishing cloth is very important.

b. Wash samples under running water.

c. Drop alcohol on the sample surface to drive water to the edges and soak it up with tissue paper.

d. Gently wipe the alcohol-coated sample surface dry with a fresh piece of tissue paper. The use of alcohol prevents damage to the sample surface.

5. Etch samples

a. Etch samples with 3-5% nitric acid/alcohol solution for approximately 5 seconds.

b. Wash with water. Dry using the procedure in c - d.

c. If grain boundaries are not clear, sample needs to be etched for longer.

d. If grain boundaries are severely eaten and the grains are hard to distinguish due to thick, dark boundaries, the sample has been etched too long.

i. Re-grind at 1000# until the surface is crisp and no pits are evident.

ii. Re-polish.

6. Samples are ready for metallography.

9.4 Data Collection & Analysis Procedure

9.4.1 Data Collection Procedure

Carefully imaging all 12 steps will take a long time. Accept that fact.

1. Imaging Procedure

    a. Orient the profile with bend legs facing the microscope operator. *See* Figure 24.

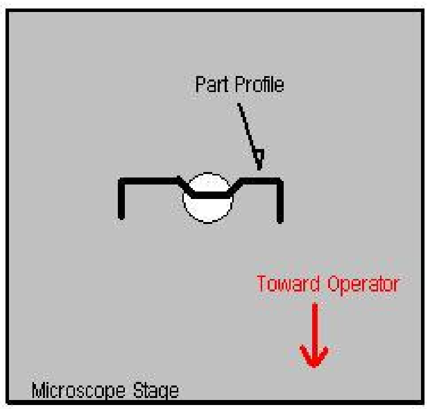

Figure 24: Orientation of the profile on the microscope stage.

    b. Use the 20/0.35 lens (green ring)

    c. Image two points on every bend

        i. Inside edge

        ii. Outside edge

        iii. Edges take up about 20% of the field of view. See Figure 25.

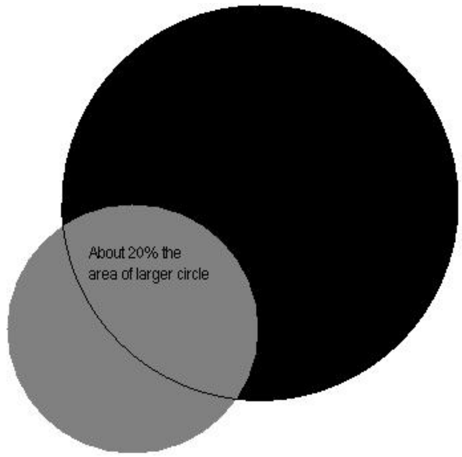

Figure 25: Illustration showing what 20% of a field of view looks like.

d. Mark next to the image field with an arrow so the orientation of the part is obvious when looking through the microscope. The arrow points toward the inside edge, and flops toward the bend to be imaged. See Figure 26.

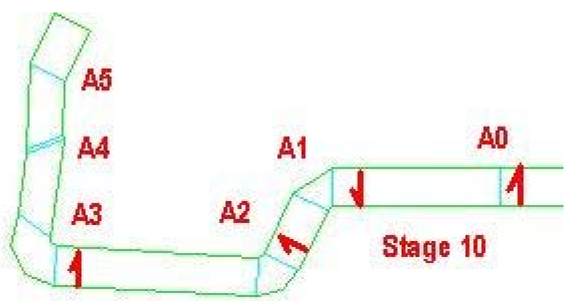

Figure 26: Technique for tracking the bend orientation while under the microscope. Arrows point toward the inside edge of a bend, and flop toward the next bend to be imaged.

2. Check that each image is in focus and clear after taking each picture.
    a. If not, re-take the picture. *Collecting good and useful data is critical.*
3. Document variables for every picture. Encode in file name.
    a. Who prepared the sample
        i. Rich Jorgenson, Jake Doucet, Bai Hua, Chen Chen: RJ, JD, BH, CC

b. Which batch sample

    i. *Batch: 1, 2, 3…*

c. Which profile is imaged *See* Figure 27.

    i. *Stage: 0, 2-12*

d. Which side of the profile? *See* Figure 27.

    i. *Side: A, B*

e. Which bend is imaged

    i. *Bend: 1-5. See* Figure 27.

    ii. *Part midpoint: 0*

    iii. *Inside edge or outside edge: I, O. See* Figure 28.

f. Syntax: <Batch>-<Stage> <Side><Bend><Location> <Preparer>.jpg

    i. *Example:* 1-02 A4O RJ.jpg

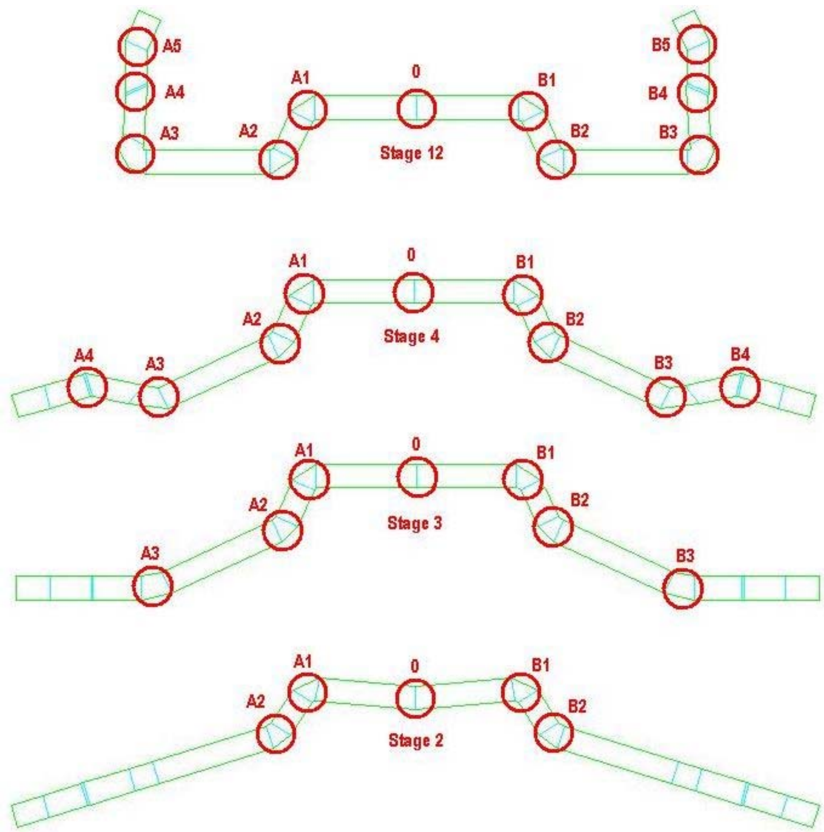

Figure 27: Locations for bend imaging.

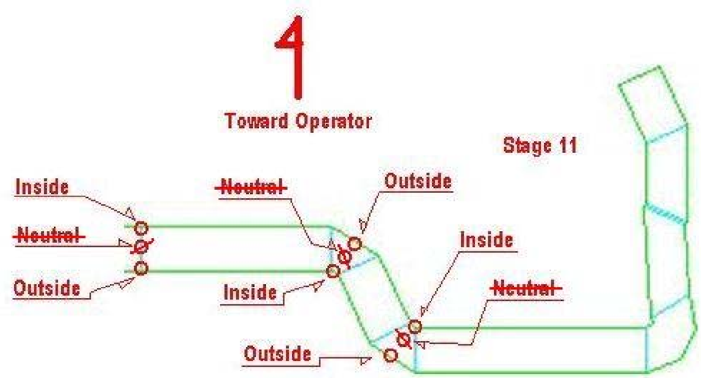

Figure 28: Field of view locations for bend imaging. Neutral field image removed from procedure.

9.4.2 Analysis Procedure

1. Import metallograph into AutoCAD

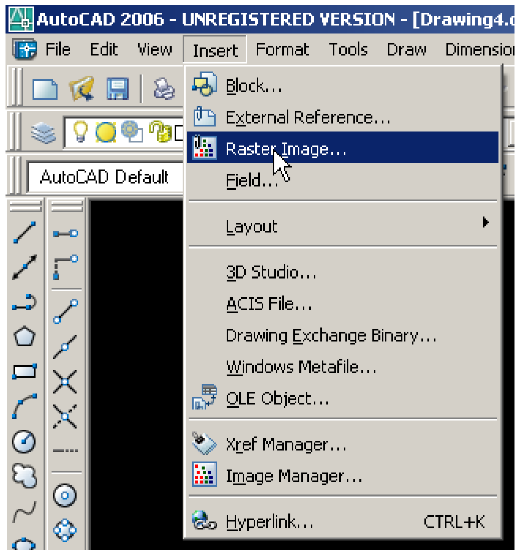

Figure 29: Importing metallograph into AutoCAD 2006

2. Set image scale factor to 200
    a. Units are irrelevant
    b. Scale factor corresponds to microscope magnification

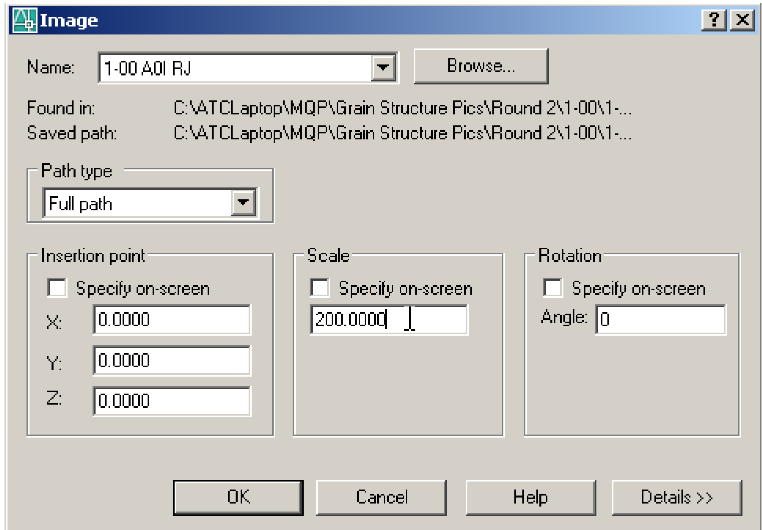

Figure 30: Setting image scale factor to correspond with microscope magnification

3. Copy the image 4 times in the AutoCAD sheet
   a. One image for each of four linear orientations 0^{o}, 45^{o}, 90^{o}, 135^{o}
   b. Reduces confusion, and tracks which lines are used, maybe for future reference.

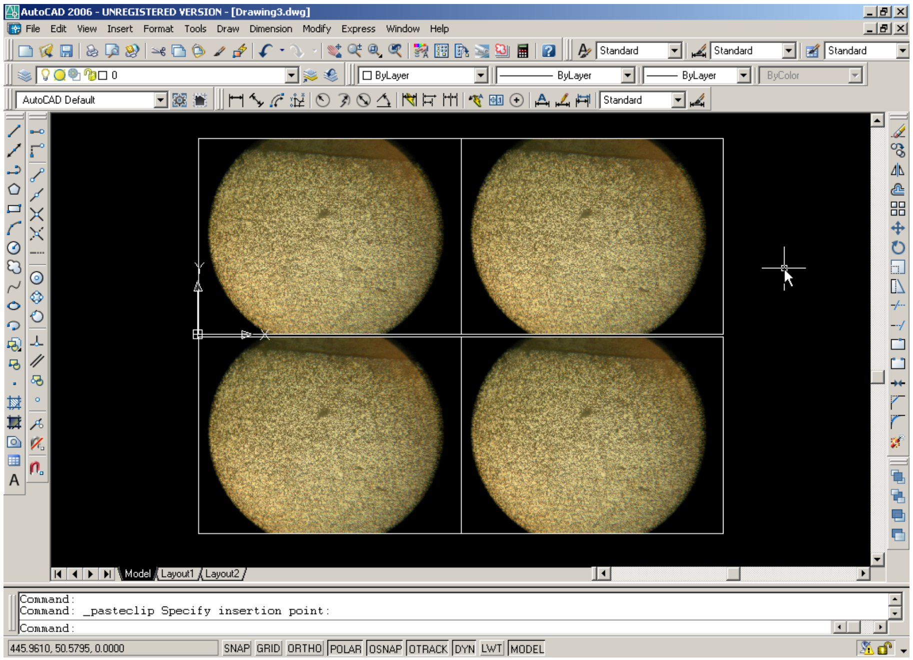

Figure 31: Copying the image four times, one image for each linear direction

4. Begin analyzing the first image by bisecting the picture with a line (for example, a 0^{o} line)

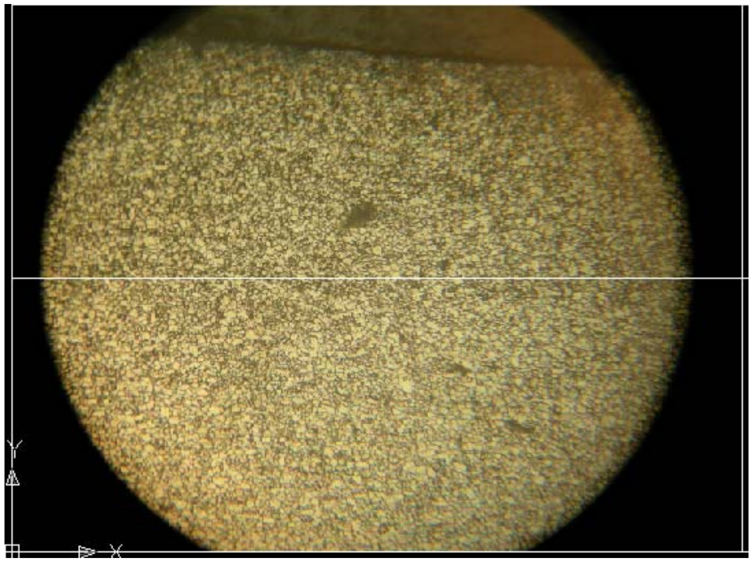

Figure 32: Bisecting the first image in preparation for analysis

5. Generate a random number (such as in Excel)
6. Place a line parallel to the bisecting line; offset a distance corresponding to the random number.
    a. The line will be 100 mm long

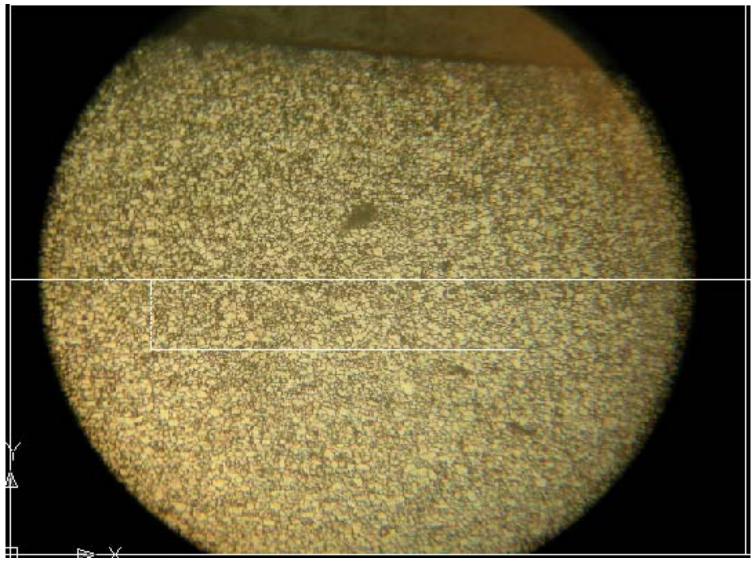

Figure 33: Adding a 100mm parallel line

7. Count the number of grains that intersect the line
    a. Add 0.5 to the count each time an endpoint lies on a grain
8. Enter the count into the Heyn method program by Meier
    a. Each line is a sample

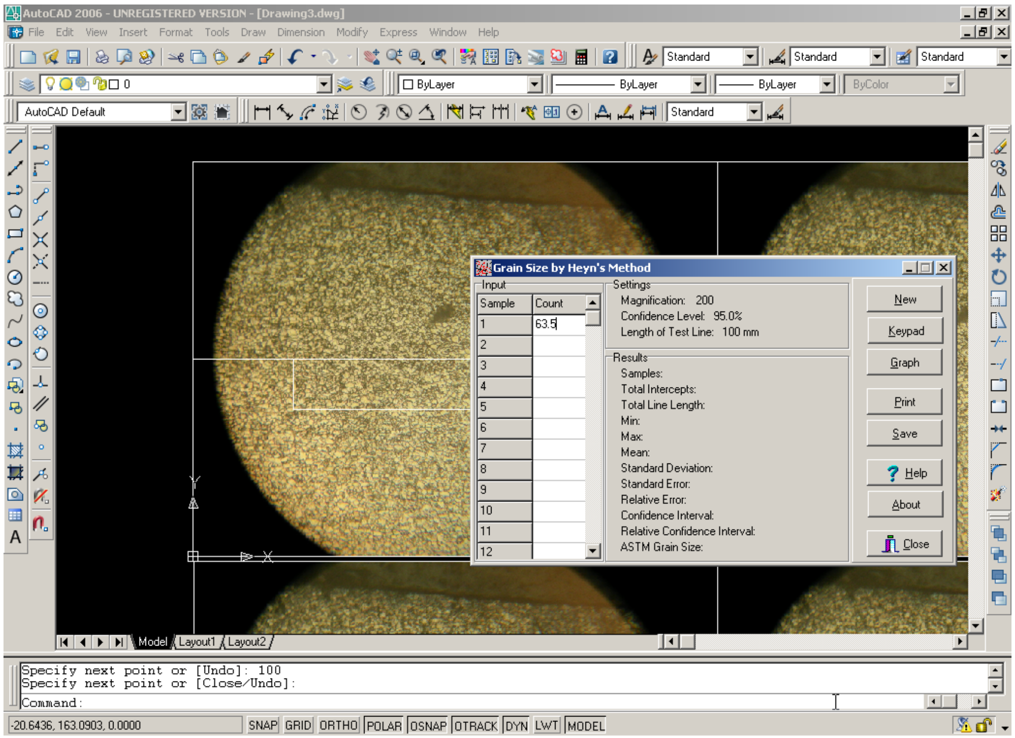

Figure 34: Recording grain count with Meier's Heyn method program

9. Take a total of 5 samples per direction, that is, draw five parallel lines and count the intersecting grains on each

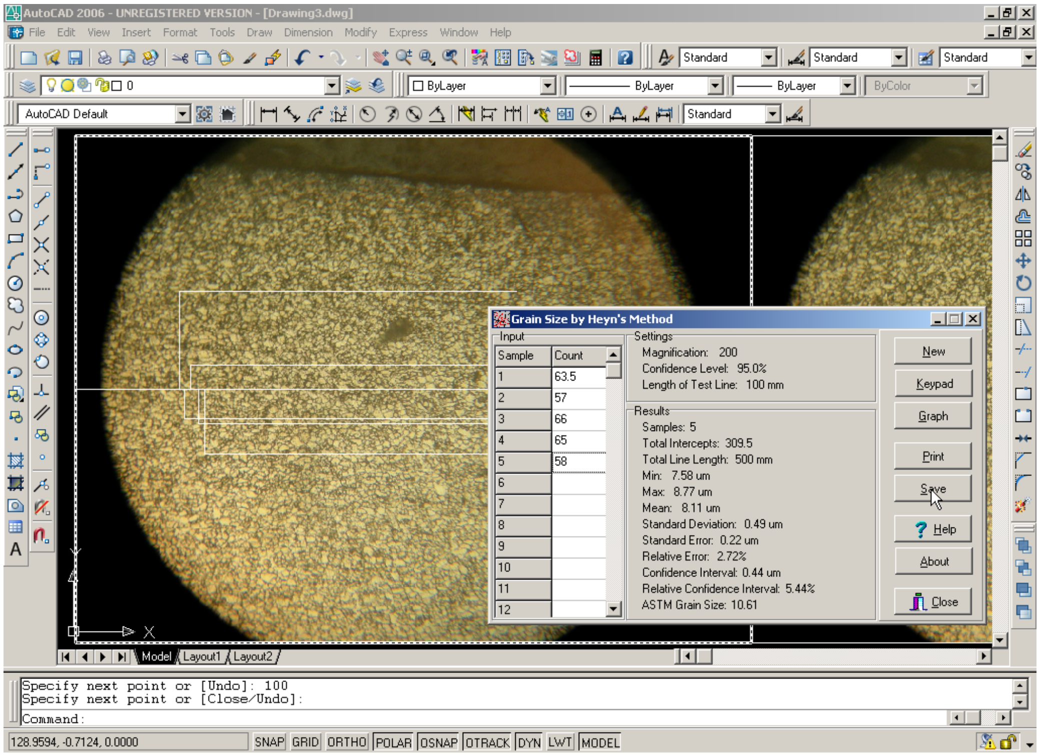

Figure 35: Recording grain counts from all five parallel lines

10. Save the results as a text file using the ‘Save’ button
11. Transfer the mean grain size, standard deviation, relative error, and relative confidence interval from the text file into the formatted Excel file

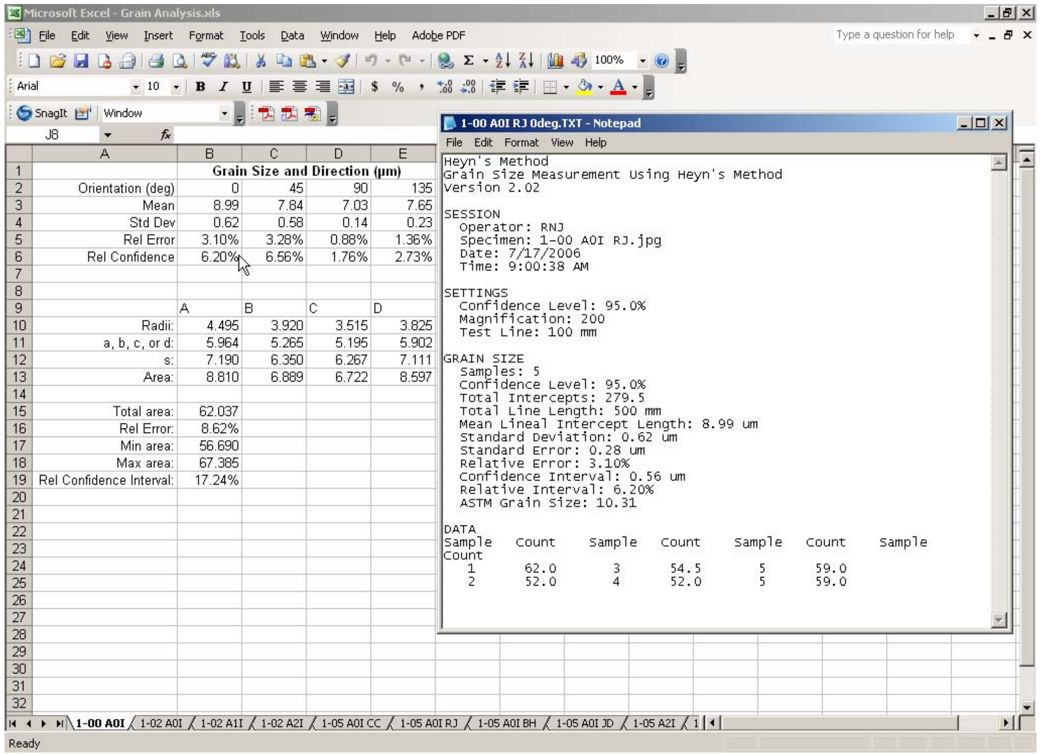

Figure 36: Transfer data into Excel for processing and analysis

12. Repeat steps 4 - 9 for each of the four directions
    a. 0^{o}, 45^{o}, 90^{o}, 135^{o}
13. Average grain area is automatically calculated, along with relative error, and minimum and maximum average grain areas.
    a. Calculated by summing triangles created by measurements in each of the four directions.

9.4.2.1 Comments on Analysis Procedure

Strengths

1. The Heyn method is robust. It seems to be pretty tolerant of grain structure variation

Weaknesses

1. Degree of variability within and between images
    a. Due to out-of-focus regions, inconsistent etching, and sometimes surface imperfections
2. Grain counting is somewhat subjective due to small grains, areas that may come very close to the line, blurry areas, and surface defects
    a. Results can vary widely between analysts. A single analyst can get good results if his personal method is kept consistent.

Strengthening the Analysis

1. To get an idea of variation between analysts, and to put a number to the degree of subjectivity, we ran a test.
    a. Each member counted the same set of lines on the same field of view.
    b. Grain counts were tallied and graphed. The lines are the same, so any variation in the counts is due to the judgment of each analyst.
    c. There appears to be significant variation between analysts.
2. To get an idea of variation between etch times, we will run another test.
    a. Pictures at different etch times for the same specimen.

Notes

1. Average grain area is calculated by using triangle geometry.
    a. Mean grain size is used to calculate the area
    b. The grain size measurement has some error associated with it
    c. Error will propagate through the calculations
        i. According to Wolfram, relative error is additive when terms are multiplied.
        ii. Is this accurate? What kind of error analysis techniques should we be using?