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Edge-Wave Formation During Multi-Stand Tube Mill Operation

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EDGE-WAVE FORMATION DURING MULTI-STAND TUBE MILL OPERATION

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MATERIALS SCIENCE AND ENGINEERING

ABSTRACT

Cold-Formed (CF), High-Frequency (HF), Electric-Resistance-Welded (ERW) tubing is manufactured using a continuous roll forming process where a flat steel strip is progressively formed into a round which is then passed through an induction coil to be heated prior to having the heated edges forged to make a weld. A somewhat common issue, particularly as the thickness decreases and outside dimension increases, is an elastic edge wave that ultimately sets into a plastically deformed strip edge that cannot be successfully joined into a welded tube. Many variables can cause or exacerbate this effect including strip not centered in the mill, significant thickness variation across the width of the strip, tooling not properly lined up in the mill and tooling design issues.

Herein, material properties and tube mill lateral alignment are examined regarding the formation of edge wave and poor quality. Material properties, within a specific range, do not have a noticeable impact on poor quality. Tube mill alignment (in the horizontal plane) does have a noticeable impact and poor alignment does contribute to the formation of edge wave.

DEDICATION

As with all things, my wife is a constant source of encouragement and happiness. And, without the general attitude of never giving up imparted by my parents, this work would never have been completed.

ACKNOWLEDGMENTS

I am honored to have this opportunity to thank the many colleagues, friends and faculty members who have helped me throughout this project. I am particularly indebted to John Montgomery, Jr. and the team at Southland Tube, Inc. granting me this opportunity to continue my educational progress. This work would never have been completed without the thoughtful contributions of my advisor, Dr. Charles Monroe along with my committee members: Dr. Robin Foley and Dr. Haibin Ning for their invaluable input, inspirational discussions and unwavering support of this thesis and my academic career. I would also like to thank Chunlei Wang for translating a tremendously aged document written in a language with which I have zero familiarity.

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LIST OF ABBREVIATIONS, TERMS AND SYMBOLS

Camber	Longitudinal curvature of the skelp
CF, HF, ERW	Cold-Formed, High-Frequency, Electric-Resistance-Welded
Crown	Condition where the middle of steel strip is thicker than the edges
D / T	Diameter to Thickness ratio of a tube
Grade 50	50,000 pounds per square inch (ksi), minimum yield strength
Grade 75	75,000 pounds per square inch (ksi), minimum yield strength
HSLA	High-Strength, Low-Alloy
ksi	kilo-pounds per square inch
SAE	Society of Automotive Engineers
Section and Gauge	The final outside dimensions and thickness of a tube
Skelp	Steel strip used as the raw material for the tube-making operation
Wedge	Condition where one edge of steel strip is thicker than the other

INTRODUCTION

Cold-Formed (CF), High-Frequency (HF) Electric-Resistance-Welded (ERW) Tube Making is generally accomplished as outlined in **Figure 1**.

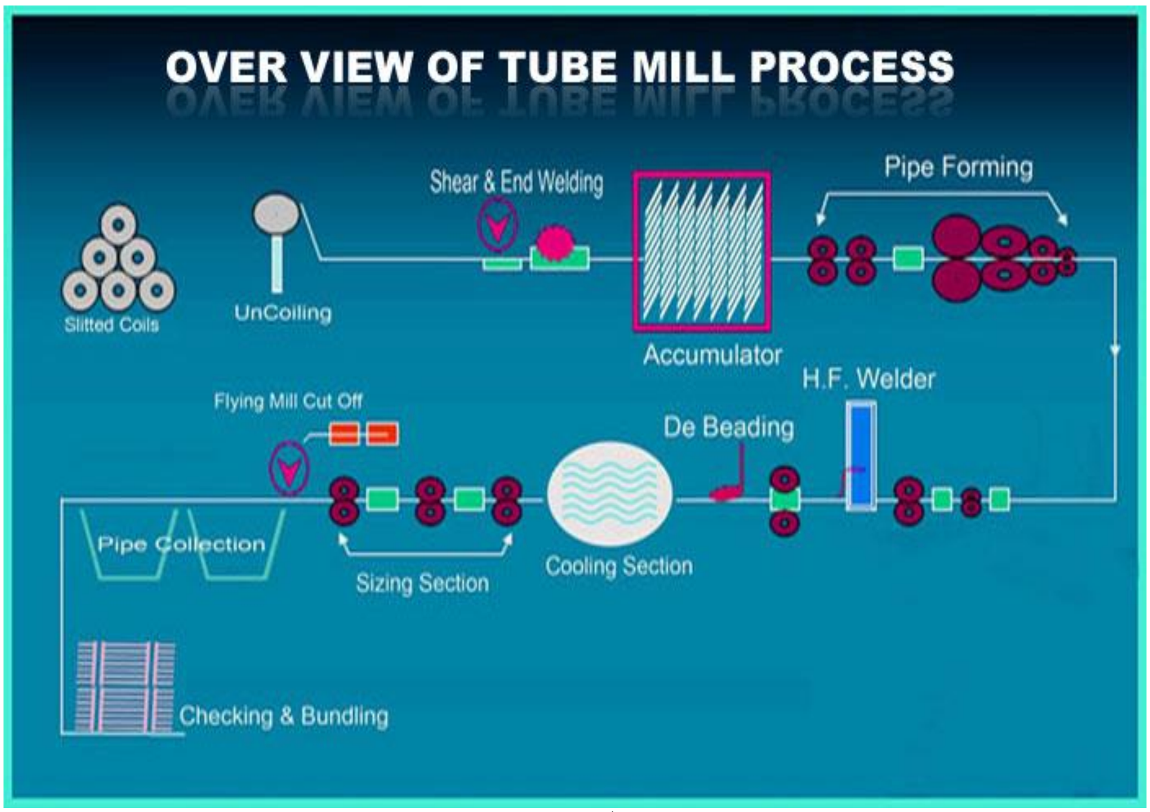

Figure 1. General layout of an ERW tube mill.[1]

Steel is generally brought to the tube making facility as master coils. These master coils are predominantly ordered by steel chemistry, width and thickness (gauge). The steel chemistry is important as it plays a large role in expected mechanical properties (tensile strength, yield strength, elongation, hardness, impact properties, etc.). The width of the master coil is computed by how many discrete widths (mults) you wish to have once you are done slitting.

Slitting is the process by which you convert one master coil into several mults, children or slit coils pending local terminology. For example, if you wanted four 12-inch mults, you would order your master coil a little wider than 48 inches to allow for losses during the process while minimizing yield loss to excess width. The thickness is ordered from the steel mill to meet the gauge requirements of the finished goods to be manufactured.

Once the master coil is slit into mults, tube making is ready to begin in earnest. The production run is quantified, and the correct quantity of slit coil is reserved. The first stop for the steel on its way to becoming a tube is the end-welder.

The end-welder is the point of the process where it changes from batch manufacturing (one discrete length at a time) to continuous manufacturing. The first slit coil fed into the process is not head-cropped (cutting the leading edge from the strip). This slit coil is fed straight to the accumulator (a bit of process equipment that acts as a surge hopper) which feeds steel in one end, contains a large quantity of it and delivers it (at a controlled rate) out the other end to the entry section of the tube mill forming stands. Then, the tail of the coil just fed into the mill is cropped before being joined to the freshly cropped head of the next coil coming into the mill.

Past this, the tube mill generally has three sections. These sections of a tube mill have tooling stands that pull and form simultaneously. The tube mill only wishes to pull the sheet metal through it and ultimately form it into a round shape. The tube forming process is not intentionally set to alter the thickness of the steel.

The first section is called the break down (and/or forming) section and it is where the flat steel begins to be curved into a round shape. The rolls in this section start with a shallow concave/convex set and progress to greater curvature as it proceeds to the high-frequency induction welding station. This section begins the work by creating a rounded 'U' shape or a gentle 'W' shape and finishes it with a nearly closed round shape. An example roll-pair (that would create a 'W') is shown in **Figure 2**. The use of 'U' or 'W' shapes in the initial breakdown rolls is a choice made by the tube mill owners.

The 'U'-shape (Straight Edgeform Method) is commonly used on a wide range of products. While the 'W'-style is used for high-strength, very light gauge or very heavy gauge finished goods. And, the Versatile Method (another method for creating the 'U'-shape) would be used for light-gauge mild steel.[2] One manufacturer claims "W-style can form more of the strip in the first pass than Edgeform or Versatile designs. It pre-forms more of the strip, giving greater stability, and provides a better presentation into the fin passes".[3]

As contact surface diminishes, the ability for the skelp to slide (laterally) increases. With proper set up and alignment, the skelp is much more likely to proceed through the tube mill in a linear and controlled fashion. Without proper set up and alignment, the tube mill is likely to encounter edge wave, off-center seam alignment and other impediments to quality tube production. It is in breakdown and initial forming where proper presentation to the weld head begins.

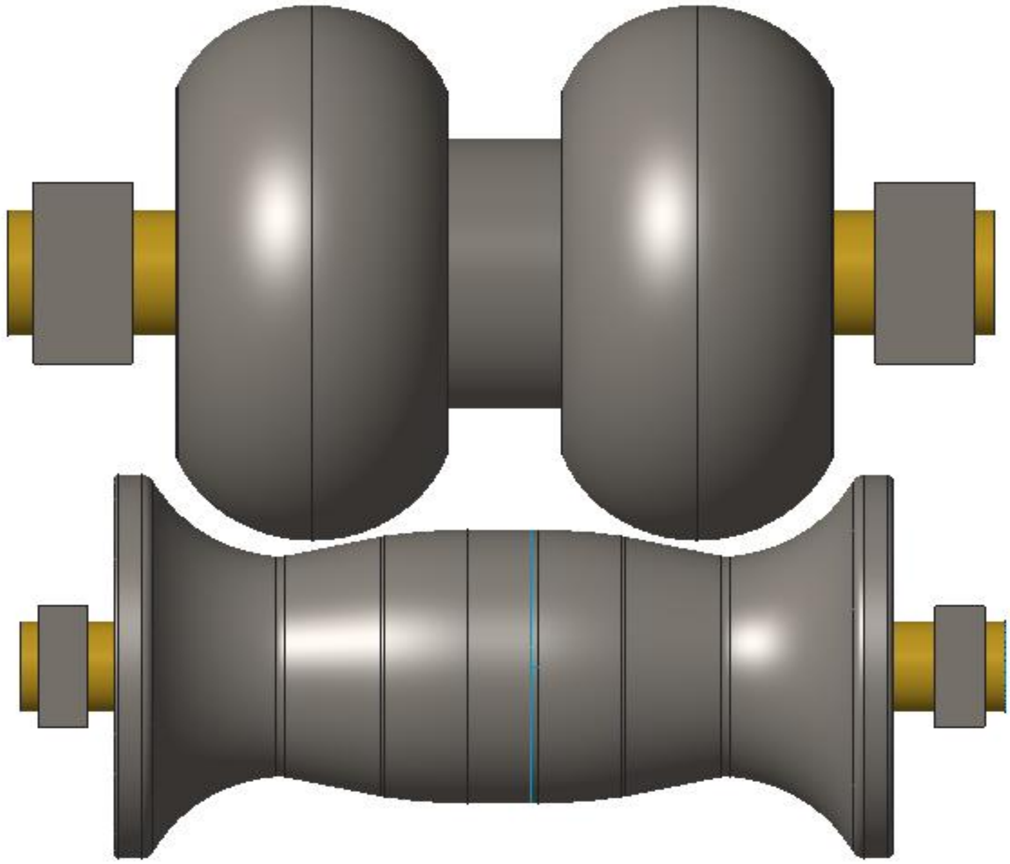

Figure 2. A rendered roll-pair. In this case, it is an initial breakdown roll pair (a ‘W’ shape here) for making a 5” x 5” x 0.120” square tube.

The next forming operation is the fin section. Shown in **Figure 3**[4], “The primary job of the fin section on any tube or pipe mill is to prepare the edges of the strip (parallel) for welding and set the body of the tube. The only way this will take place, is if we properly set (work) each and every driven and side pass station in the fin section as per the tooling design and set up chart.” [4] This section brings the strip edges to nearly touching (full closure). Between the end of the fin section and weld stand, the strip edges are heated.

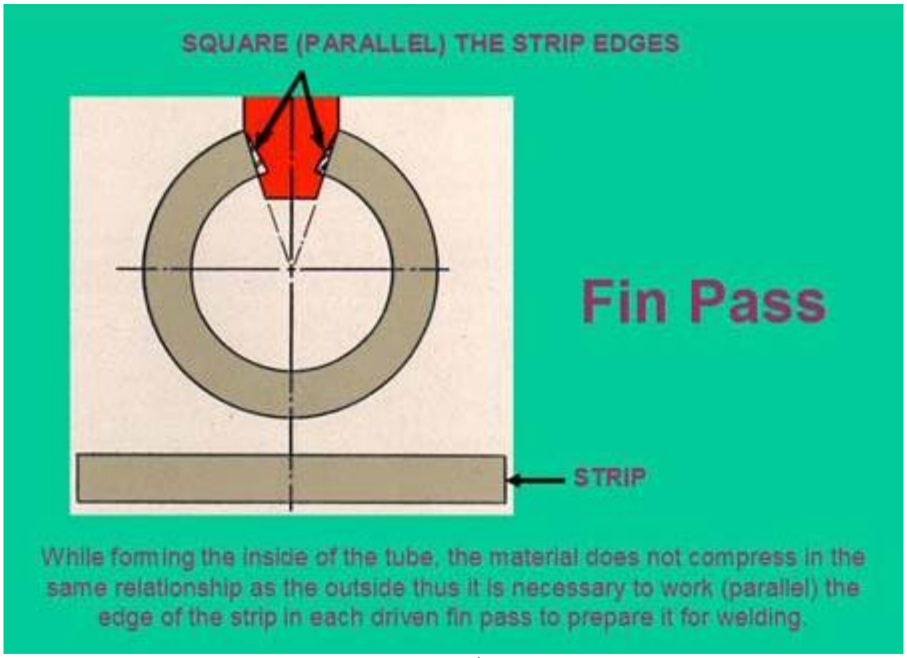

Figure 3. Purpose of the fin section. [4]

In the 'high-frequency, electric-resistance-welding' manufacture of steel tubing, the closing round shape is then passed through an induction coil. This coil (combined with an impeder to help direct the flow of energy) induces a current in the strip which collects at the strip edges and heats these edges to the welding (forge welding) temperature. The strip edges are not heated to the melting point. To minimize weld defects, the strip edges must not be heated to the melting point. This heating is completed at the point where the strip edges meet. These edges meet at the weld rolls which are just past the induction coil forming the tip of the weld 'vee'. The weld stand consists of one set of forging rolls. These rolls take the heated strip edges and forge them together into a forged weld that uses nothing but parent metal in the creation of the weld (**Figure 4**). Once the tube is welded together, it is now generally termed a mother tube.

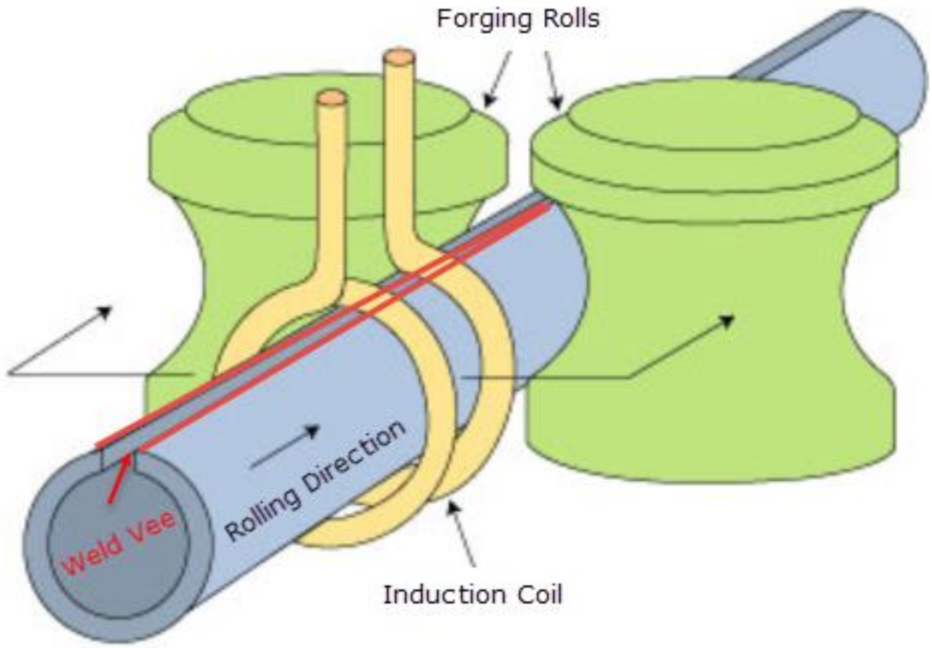

Figure 4. Tube welding stand, descriptions added by this author.[5]

If the strip edges do not meet in a parallel, vertical and closing fashion, a proper weld is not likely. Edge wave and springback are two conditions that contribute to poor welds. "We also must insure we have a 'round' welded tube size, which is the way most weld roll tooling is designed…Common sense will tell us that in order to have a successful welded tube/pipe; we must first insure we have set up the breakdown and fin sections properly…"[6]

As the seams are pressed together creating the weld, material is pushed out of the plane of the strip thickness and is generally known as flash or bead. This material is generally pushed both to the outside of the tube and the inside of the tube. Flash control (also called de-beading) is the process by which the extruded flash is removed. Practically, it is always removed on the exterior of the tube (OD Flash Control) to present a smooth surface. It can also be removed from the interior of the tube (ID Flash Control) to give a uniform height of interior flash. The interior flash is generally removed for end-users who wish to insert other tubes or manufactured pieces into the ends of the tubes.

The last section is termed the forming section and is where the mother tube is formed to its final shape and dimensions. If the final shape is to be round, these stands further refine the roundness and outside dimensions of the finished tube. If the final shape is other than round, these stands progressively form the tube into its final shape and outside dimension.

After the forming section, the sized and shaped tube is cut to discrete lengths, packaged and shipped on to various end points. Somewhere in the last few steps, a tube sample will be harvested for weld quality, dimensional and laboratory inspections.

As seen throughout the literature, much work has been done on proper tool design to avoid shaping issues. dataM Copra™ gave a presentation[8] on their software's abilities including a demonstration of eradicating edge wave which is a condition preventing successful forming and welding operations. Edge wave is generally caused or exacerbated by upset strain conditions created during tube forming. An example of permanently-set edge wave can be seen in **Figure 5**.

In the case seen in **Figure 5**, the cause is attributed to tooling design. This exact problem can also be created by tube mill misalignment. As the strip winds its way through a non-linear path, it will bend in the horizontal plane (camber). Camber is not fully possible as the downstream forming stands constrain its creation. As the camber is constrained, the skelp edges experience strain and tend to "hump up" into a wave pattern.


Figure 5. The final plastically deformed state of edge wave in an ERW tube mill.[7]

Quality problems affecting the financial bottom line of a business are often manifested as yield losses. Not to be confused with the material property ‘yield strength’, yield (sometimes called finished goods yield or process yield) is a common measure by which industrial manufacturing gauges its efficiency. And, in this case, is calculated by the pounds of finished goods created from the number of pounds of raw material. For instance, 40,000 pounds of finished tubing from a 50,000-pound master coil would indicate a, full process yield of 80 percent.

“Poor mill alignment. 95% of all tube-related problems are attributable to mill condition, setup and tube mill alignment.”[8]

LITERATURE REVIEW

Industry Partners

Several industry partners publish work relating to their business or supply. Oftentimes these sources serve a dual-purpose. While they are generally considered commercial tools, they are also quite instructive regarding the current state of the industry and the use of the products.

Roll-Kraft

Roll-Kraft, a tube mill equipment manufacturer, plainly states on their website[9] that inconsistent incoming material, misalignment and improper setup affect scrap on a tube or pipe mill. In other areas of their website, the discuss material selection and setups.

- Inconsistent incoming material, which includes chemistry, slit edge condition, strip width-to-gauge tolerance, crown, and camber. At all times, it is important to maintain ordering and receiving standards to identify and avoid these core complications.
- Misalignment of entry strip to first breakdown. Off-centered strip will result in improper forming, especially with modified edgeform and “W-style” designs.

- Improper setup. Tooling which is not set up according to a setup chart cannot perform as designed. There is no certainty derived in setting up a mill totally by feel or using a “seat of the pants” technique.
- Poor mill alignment. When was the last time the mills were aligned? The standard in the industry is to have mills aligned annually or after performing any major preventative maintenance.

Thermatool

Thermatool is a member of the Inductotherm group and is a tube mill equipment manufacturer. They often specialize in welding technology; but, they have done considerable study on the presentation of the strip edges to the welder.

In Robert K. Nichols book, High Frequency Pipe & Tube Welding[10], some sources of poor quality are considered within “The Effects of Steel Mill Practice on Pipe and Tube Making”.

- “When steel is rolled on a continuous mill, gage control is somewhat better due to the rigidity of the rolls and stands. This means that crown is less and edges are more uniform than for reversing mill product. The result of this is the edges of multi-slit skelp are nearly the same thickness resulting in straighter and more uniform slits. Also, the lead and trail ends of continuous mill skelp are less likely to be thicker or thinner than the center.”

    - Reversing mills do produce high-quality strip. However, this process is more prone to upset as it is a more complicated set up than single-pass rolling mills.
- "Chemistry can have a significant effect on formability of steel. Higher carbon and alloy steel tends to get harder as they cool from the rolling/ finishing temperature. Harder steel is stronger (stiffer) and therefore will exhibit more springback between the last fin roll and the weld rolls."
    - Residual elements such as Sn, Cu and Ni all influence material properties and can vary wildly from heat to heat during steelmaking.

data M

data M Sheet Metal Solutions is a FEA software developer that has a very specific software, Copra® RF Tubes, "used to simulate the roll forming operation by non-linear elastoplastic calculation"[11].

- Copra® RF Tubes is a "Tube Mill Roll Design Center"[12]
    - This software is designed as a tube mill tooling design package. This sort of work is outside the scope of this paper's intent. However, it does provide a clear indication that improper tooling can give some very real quality issues.
- From dataM's Copra® presentation[7], a model is shown indicating that tooling is causing excessive strain as the strip exits a forming stand leading to a permanent set edge wave. Further, it describes that with some undisclosed changes to the

tooling these strains are made more uniform and eliminate the edge wave previously noted.

Academic Publications

Augmenting industry resources, some academic work has been done to investigate weld quality issues and proper tooling design. Many located resources mention misalignment as a source of poor quality with very little quantitative work done. A typical example found in a discussion of weld mismatch, where the skelp edges do not meet in perfect alignment when presented to the weld head, Bhartim[13] states, as a possible reason for mismatch, Mill Alignment.[13] As in most of the discovered resources, mill alignment is important but very little work has been done to quantify its limits.

When considering proper tool design, most assume linear alignment. In "Geometric constraints…"[14] Panton, et al. discuss the concept of bend angle as important in tooling design for a roll forming process (a channel in this case), they specifically hold linear alignment fixed and perfect. In manufacturing, fixed and perfect does not often exist.

A deep discussion of edge buckling is found in work done by Toyooka, T.[15]. In the dissertation, the author describes the creation of roll-forming software (CADFORM) to be used as a tooling design software. The author holds linear alignment while fully describing the mathematical conditions for the creation of edge wave (buckling) caused by improper tooling.

Camber is described as “longitudinal curvature of the formed profile along the y and x axes respectively”[16] and that it “depends on the difference between the residual strains at the edges and center of the formed strip cross section.”[16] These authors also posit that edge wave can be eliminated by “straightening the profile”[16]. They also report “the edge waves are the result of either bending, compression or torsion of the strip within the CRF process. The edge waves (due to strip buckling in the edge regions of the formed strip) are caused by the maldistribution of the longitudinal plastic strains across the strip, where the edges are overstretched by unfit rolls, (during the CRF process) and subjected to the compression from the side of the less stretched regions of the strip. The maldistribution of longitudinal plastic strains may result not only in the edge wave effect, but also in bending and torsion.”[16] And, the concept of a ‘W’ shape is discussed to avoid “edge waves using a “double bending method”, when both the edges of the sheet are bent to the desired shape with W-type profile rolls of double calibers, at the initial stage of the forming process.”[16] Camber being induced by misalignment is a contributor to the edge strains that manifest as edge wave.

Baba[17] evaluates buckling and largely attributes this to tooling design and distance between forming stands. In passing, it is also mentioned that it “could be explained by the fact that the center line of hoop steel sample can shift left or right on the roller stands.[17] As stated earlier, the skelp can move laterally and is more likely to do so as the contact surface in the tooling is reduced and as mill alignment worsens.

Russell and Kuhn[18] discuss sheet bending as applied to corrugating sheet metal. In something as rudimentary as taking a sheet and corrugating it, linear alignment is assumed with the statement “the neutral axis remains at the center of the sheet”. It appears as if nonlinear alignment conditions vastly complicate the model and calculations.

Wen, B. and Pick, R.J.[19] performed modeling of vertical misalignment and investigated roll gap setting to investigate their effects on edge instabilities (buckling). The goal appears to have been better quality production of thin-walled, large-section tubes where the concern was weld quality. They appear to hold linear alignment and assume annealed strip.

Farzin, M., et al[20] describe a factor known as “buckling limit strain” as a limiting factor for edge stability as the skelp moves from flat to formed throughout the progression of the forming stands. Again, this work is aimed toward proper tooling design and not toward mill alignment. While this is the case, it is important to understand the various methods by which edge wave is formed.

It very much appears as if the body of research has been focused on either weld quality or tooling design. Vertical misalignment has been studied in a limited fashion; but, there appears to be no published work investigating lateral misalignment. None of the reviewed literature accounts for wear and poor maintenance that would allow misalignment in any direction. Very little work has been published regarding the limits of mill setup and non-linear alignment.

It seems rather obvious to one skilled in the art of tube making that alignment issues will cause problems in manufacturing. This statement of the obvious becomes clearer with each reviewed paper, with one exception, simply holding alignment perfect. In part, it simplifies the generation of tooling designs. More importantly, it becomes very complex to model misalignment.

The complexities include the lack of full contact, the changing of skelp dimensions with gauge changes, material properties that may or may not be perfectly isotropic (oftentimes skelp is simply hot-rolled steel sheet) and many more. Add to this that mill alignment is the responsibility of the tube mill owner (many of whom consider tube making to be an art and not a science) and very little academic work has been done to quantify the harm done by misalignment.

OBJECTIVES

Investigate possible contributors and work to quantify their effect on edge-wave formation. Steel properties, tube mill equipment condition and linear misalignment were given a closer inspection.

With so little work published quantifying misalignment and with the array of complexities found in a tube mill, a simple model to describe the strains associated with camber formation (and its subsequent suppression in the tube mill) is sought. With a model, even a simple one, tube mill operators can be better educated in what is allowed and what should be avoided.

EXPERIMENTAL METHODS AND MODELING

PTC Creo Parametric (and Simulate Lite)[21]

As can be seen in from the overhead view in **Figure 6**, the skelp would need to follow a torturous path to advance through these three rolls having just one roll in a state of misalignment. The misalignment here is exaggerated to make it more readily visible. The skelp modeled was taken as what would be considered a plain low carbon steel (in this case, SAE 1008) with the following properties which could be considered common for much of the steel used in a structural tube mill.

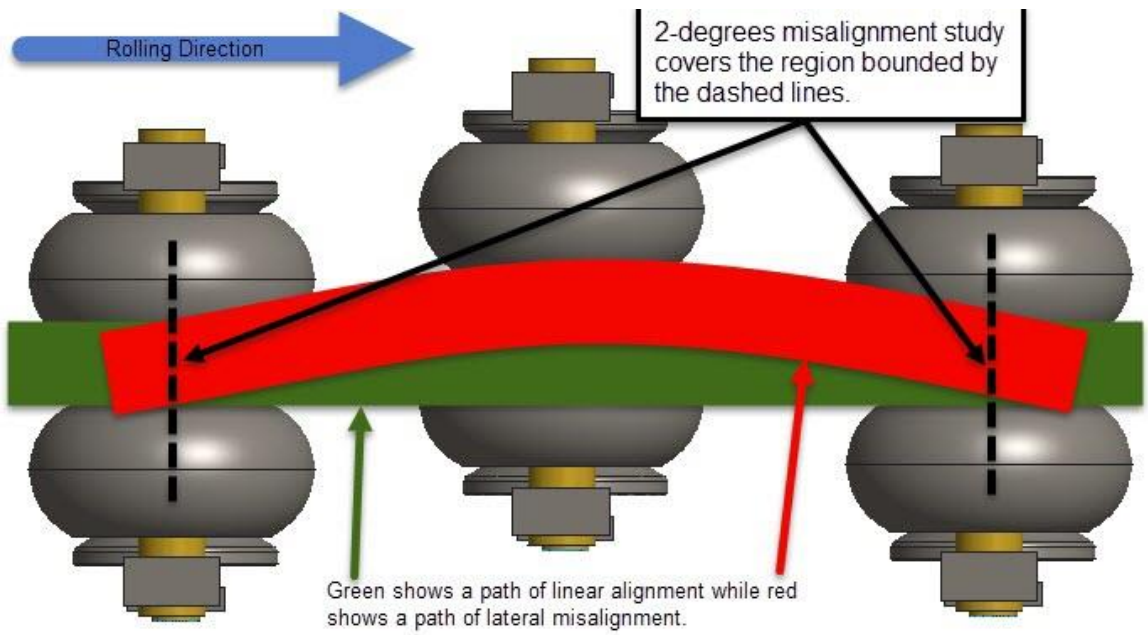

Figure 6. Overhead view showing a simple state of lateral misalignment. The blue arrow describes the rolling direction of the skelp being formed.

- Density: 0.283599 lbm/in^3
- Symmetry assumed isotropic
- Stress-Strain response assumed linear
- Poisson's Ratio: 0.285
- Young's Modulus: 29,007.5 ksi
- Tensile Yield: 41.3 ksi
- Tensile Ultimate (UTS): 49.3 ksi
- Failure Criterion: Maximum Shear Stress (Tresca)

Herein, the skelp was left flat as it would be presented to the initial breakdown stand. The ends were constrained to not allow deformation to replicate a sudden departure from alignment and a sudden reset to alignment. A lateral force sufficient to deform the metal (43.0 ksi in the case below) was applied and the model advanced until the stresses developed at the corners exceeded the UTS. At this point the model was stopped and a departure of two degrees, away from linear alignment, was measured within the software.

The model described this misalignment of 2 degrees with a sudden reset to linear alignment as a certainty of forming issues being created. **Figure 6** shows an exaggerated view of linear misalignment. **Figures 7 – 12** illustrate the model's output and generate an expectation of edge wave with misalignment in the tube mill. The displacements in the X, Y and Z-directions give an indication of the skelp deforming in all three axes. As it is stretching and bending (camber being induced), strains are developed that are expected to manifest themselves, at least partially, as edge wave.

With a tube mill having multiple forming stands (generally 8 or more) and each stand having a slightly to very different shape than the previous roll-pair, any model becomes very complex very quickly. In fact, having just three sets of rolls made the model more complex than the educational licensed software could manage. There is little doubt that with a full license version of modern software a more complex, and satisfactory, model could be developed.

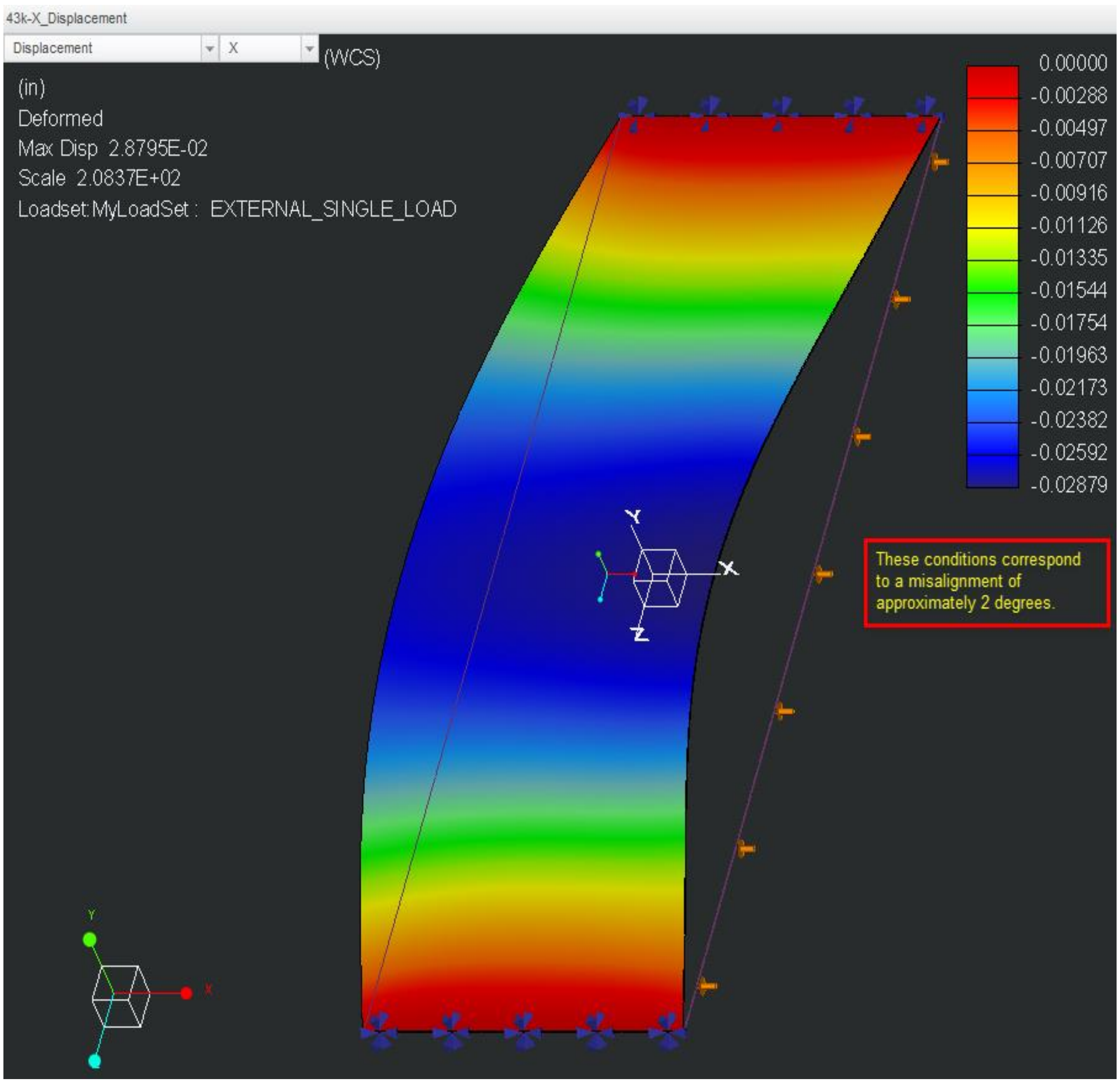

Figure 7. Displacement (negative X direction) induced by applying a constant force along the skelp edge as shown above.

The deformation in the X-direction shows the condition known as camber. It is a lack of linear straightness in the longitudinal direction.

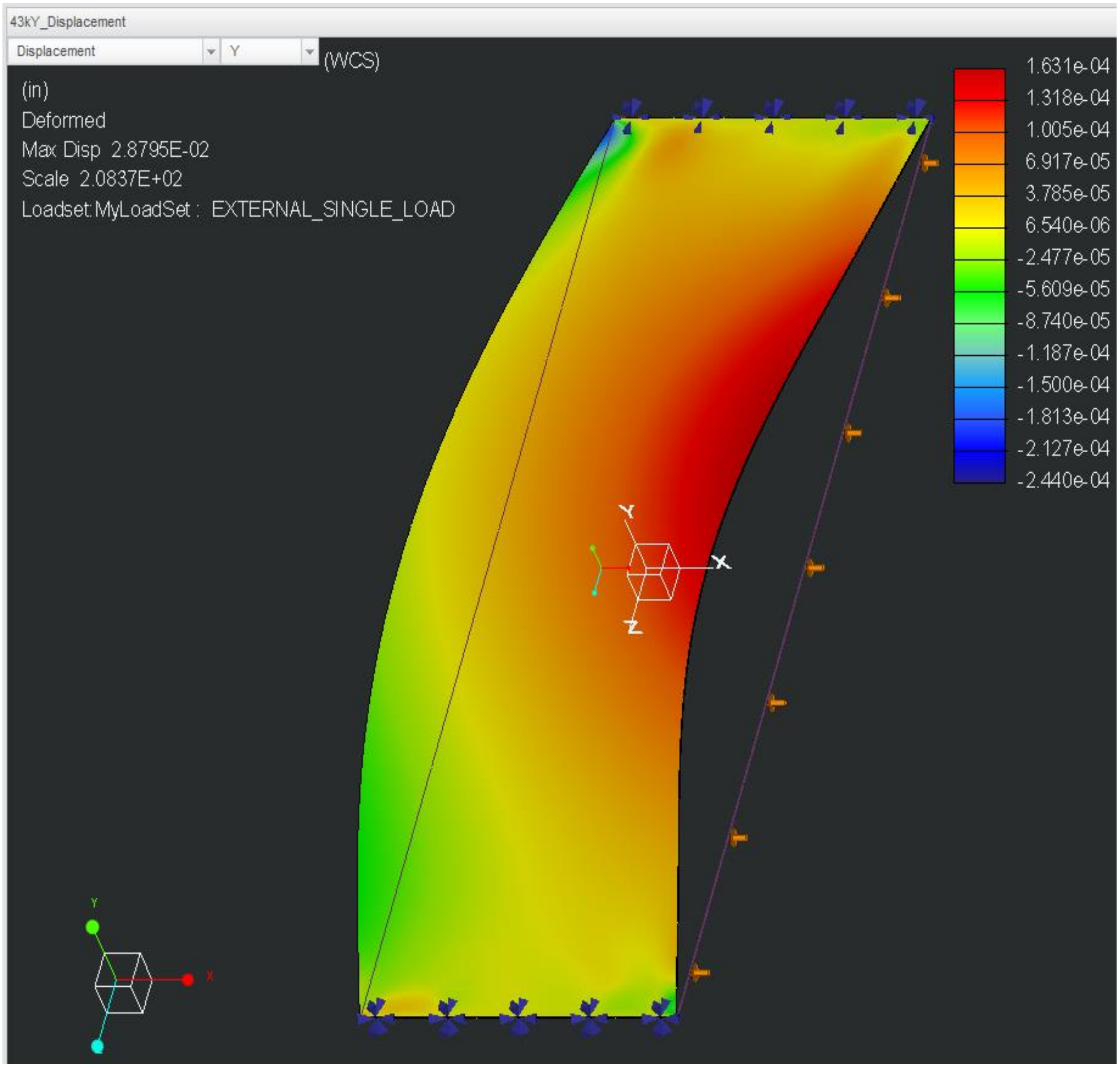

Figure 8. Displacement (Y direction) induced by applying a constant force along the skelp edge as shown above.

Here one can see small vertical deformation happening in both positive and negative (up and down) directions. Coupled with the inherent strains and the conditions are set for edge wave to occur.

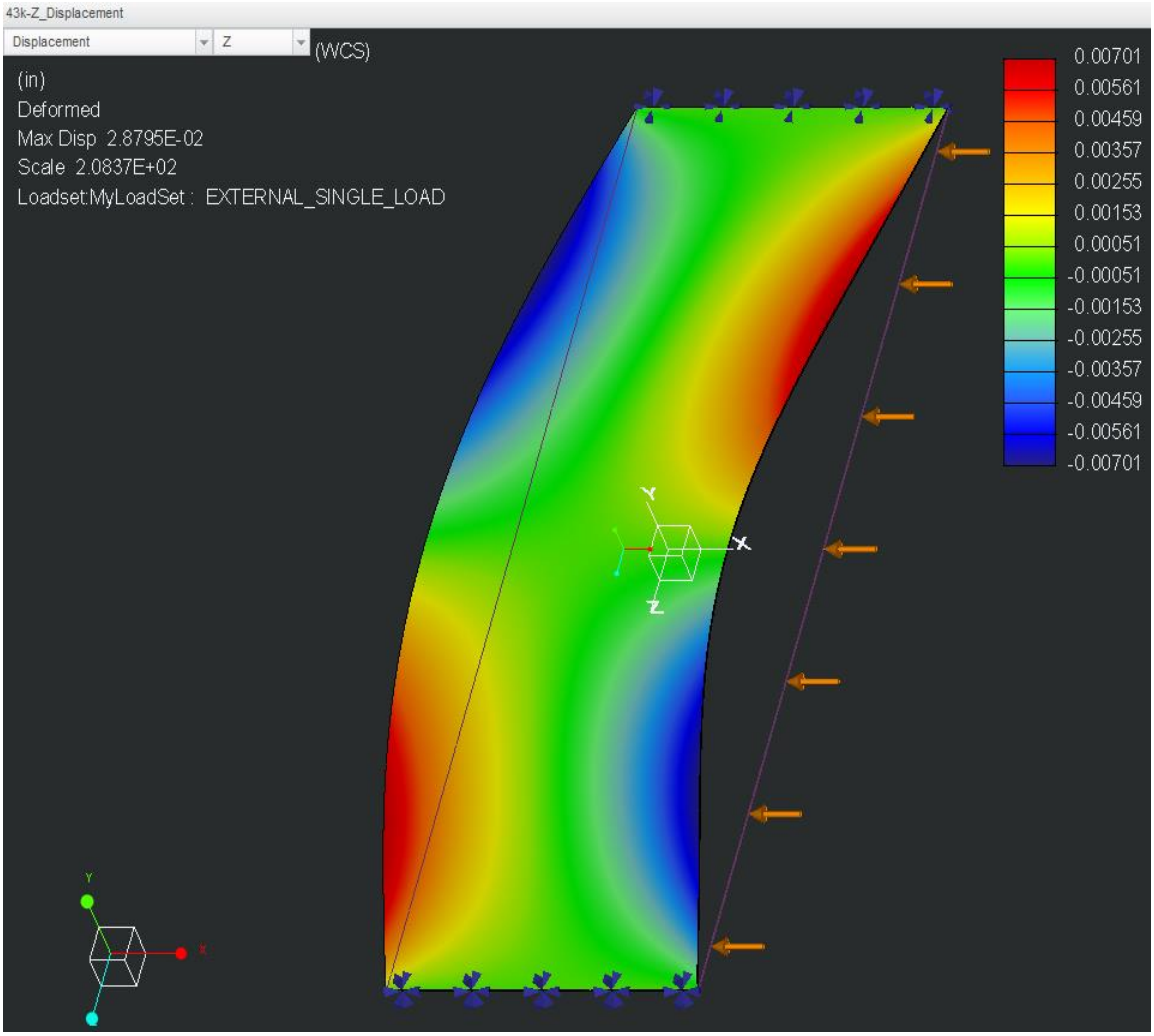

Figure 9. Displacement (Z direction) induced by applying a constant force along the skelp edge as shown above.

Here is where one sees an expected stretching and compressing of the skelp. This will manifest itself predominantly as edge wave rather than thickening and/or thinning of the skelp.

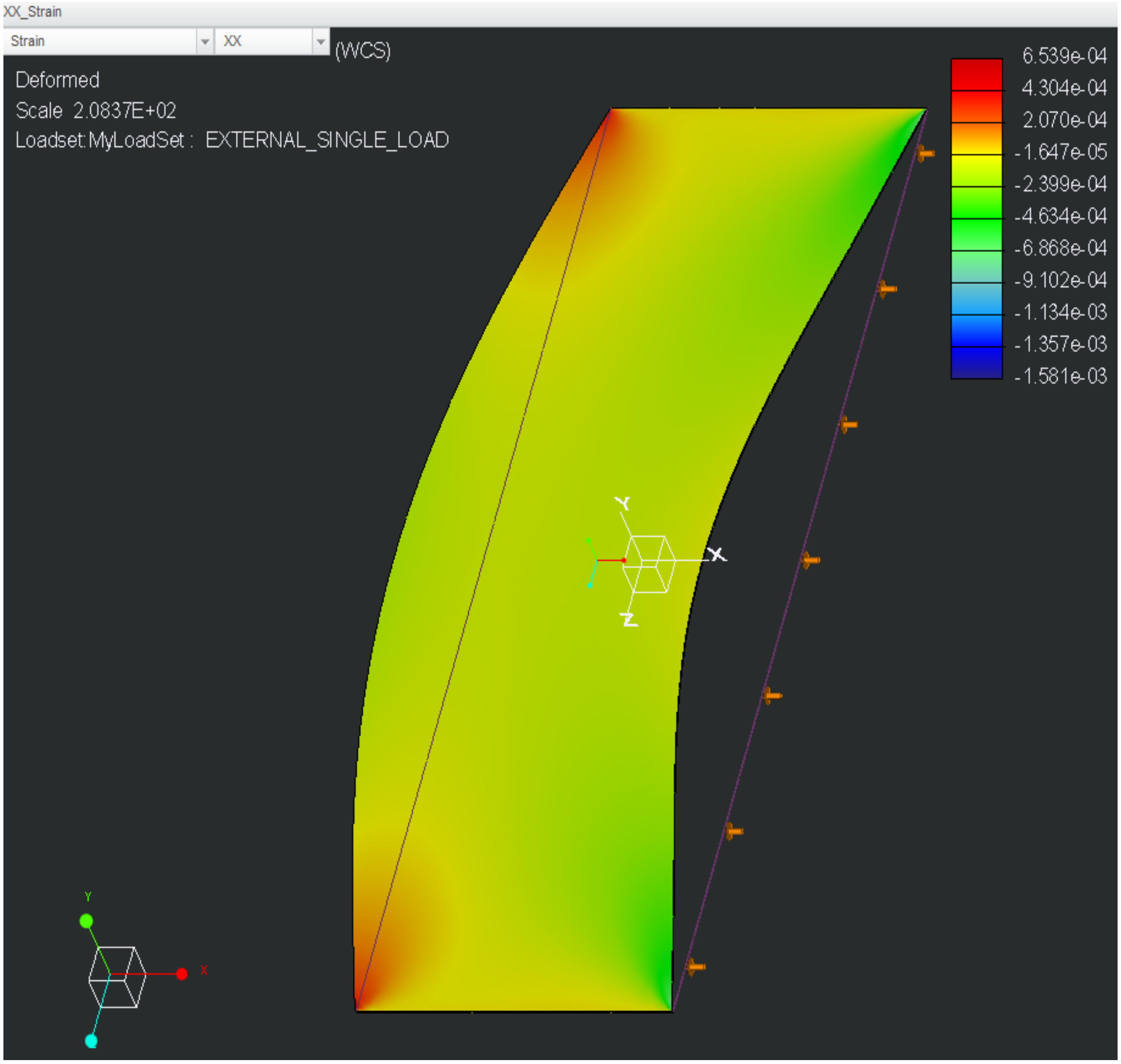

Figure 10. Strains observed within the simplified model, X-plane shown here.

The strains are relatively minor but do exist in both positive and negative directions.

These strains are induced by creating camber.

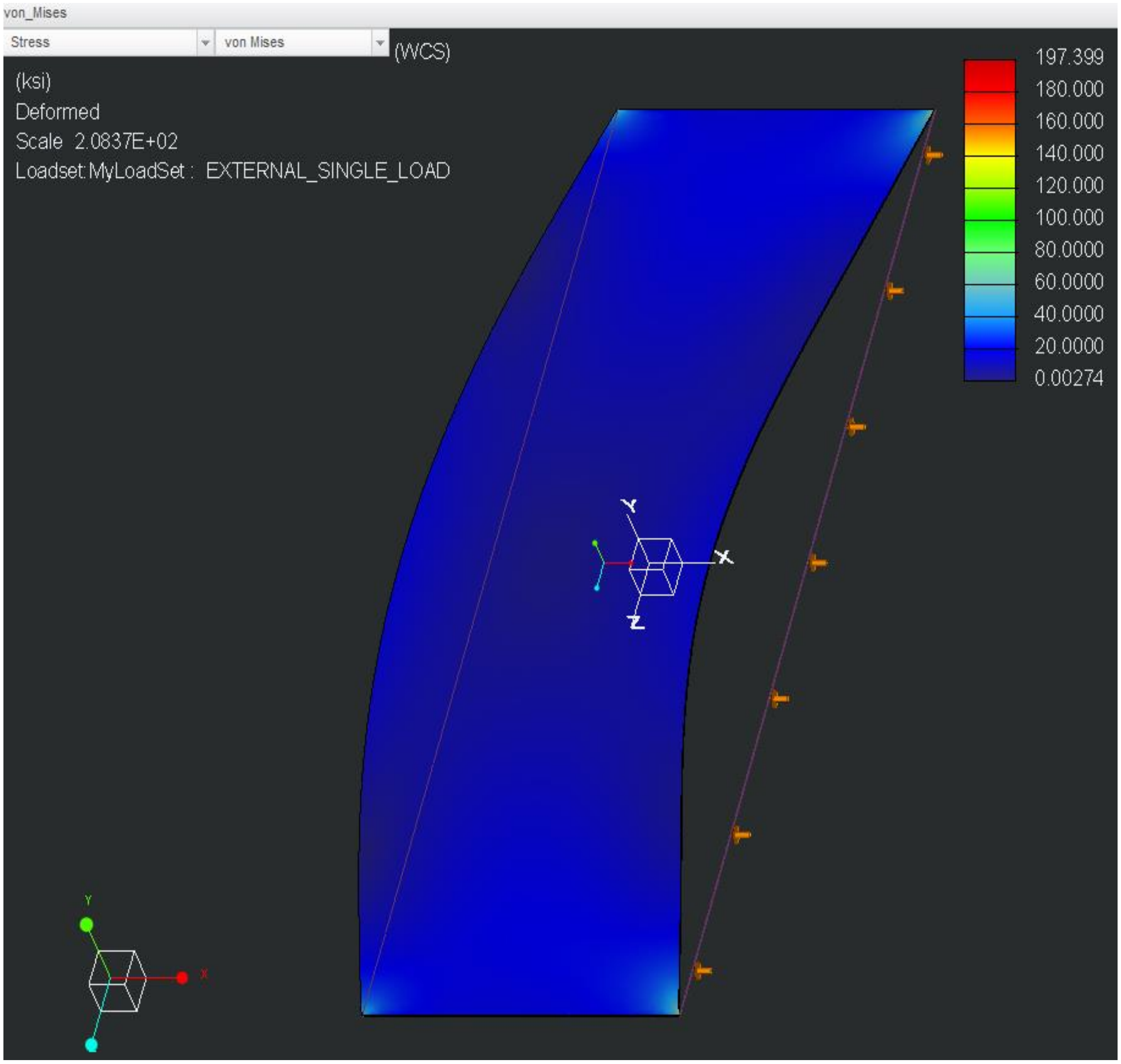

Figure 11. Von Mises Stress observed within the model.

This view gives a sense of the stresses imparted that are quite sensible when considering how the camber was induced in this model.

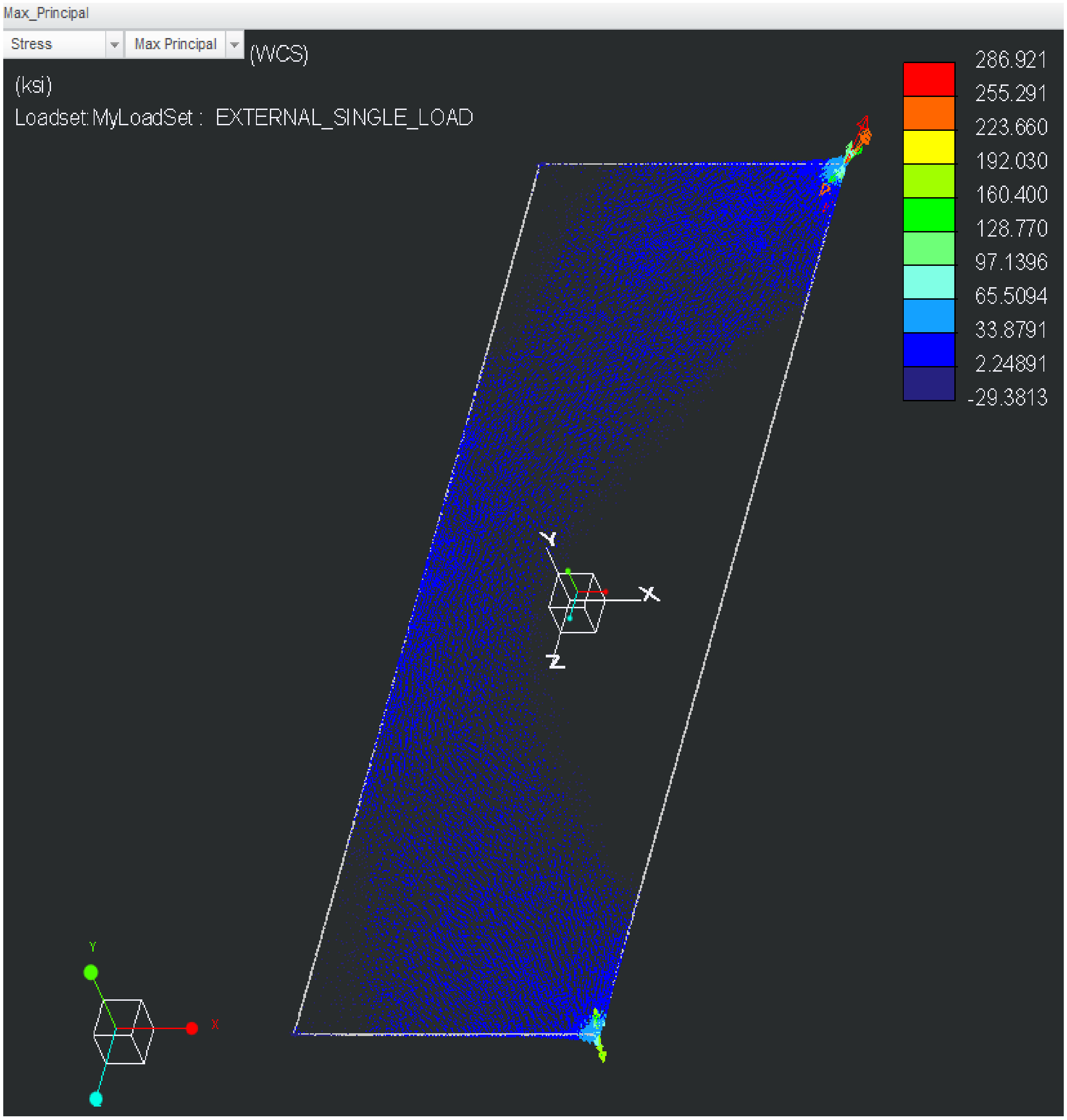

Figure 12. Max Principal Stress observed within the model.

This would indicate failure at the corners, here is one place where the simple model fails due to its constraints. By holding the narrow ends in a fixed position, the model has practically no choice but to deliver this result.

But, using this the advancement of the model could be stopped before the stresses surpassed the UTS so that an initial measurement of misalignment (that would lead to edge wave) could be made.

Figures 7 – 12 illustrate a very simple approach to compare bending between three points and forming between three misaligned points. Using this information, a tube mill was set up to replicate this two-degree departure with sudden reset and edge wave was experienced. This overly simplified model is likely to prove insufficient as a complete modeling method; but, may find utility in rough use helping to determine maintenance limits for allowable wear on tooling, bearings, etc. Using this, a tube mill having a known distance between stands of 30 inches would want less than one inch of misalignment and a sudden reset to linear alignment.

FTI – Forming Suite™ [22]

Another common complaint from tube mill operators has been that changing steel properties cause them forming issues. Without doubt that is a sensible statement except that the steel properties a tube mill tends to see during each set up are not variable in any measurable extreme. To this end, a brief forming study was completed to determine the likelihood of forming problems and springback by varying material gauge and strength within common ranges.[22] By forming a flat strip into a half-round shape using different material strength and thicknesses; and, by forming a hat shape from a flat strip little evidence of either issue was found. While a hat shape does not replicate tube forming except in its earliest steps, this was selected as it was a very simple shape to model and creates a very similar forming pattern to initial “break down” in the tube mill. **Figures 7 – 30** illustrate a lack of forming issues based on simple material property changes. This is a finding which is initially confirmed in **Figure 31**.

In more general terms it is noted that when forming the half round that material thickness and yield strength has little effect on strain (**Figures 13 & 14**). While this is not simulating a rolled condition, it shows that when no unexpected strains exist, average material properties have no appreciable effect on the success of forming.

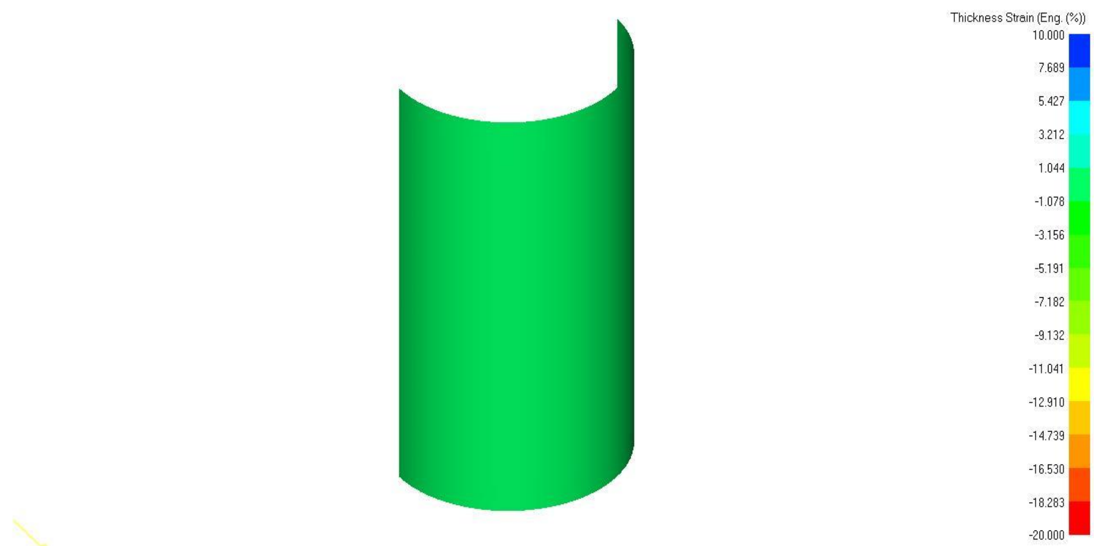

Figure 13. Three-millimeter-thick Grade 50 (50 ksi yield) HSLA (High-Strength, Low-Alloy) Steel showing nearly no thickness strain.

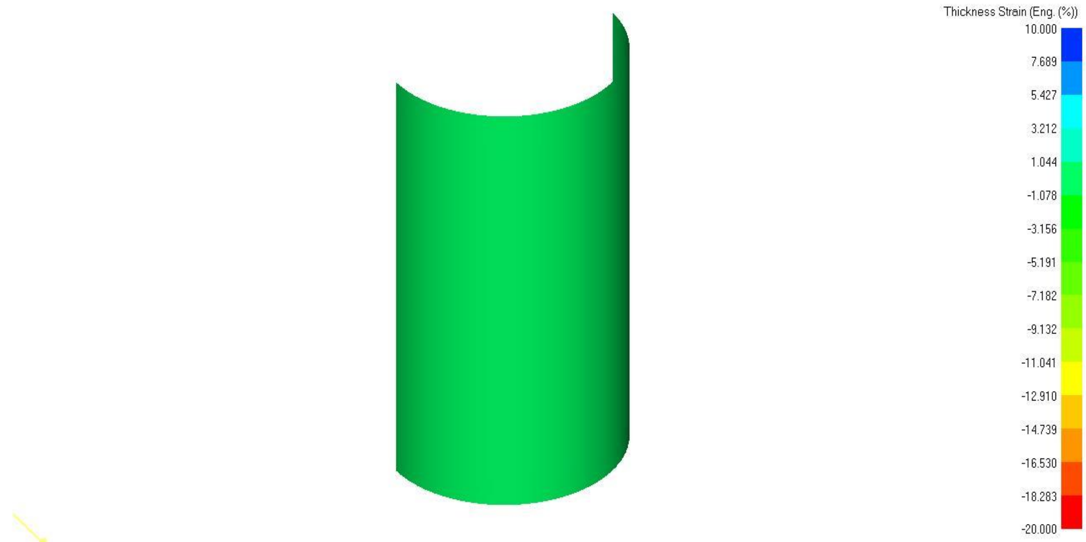

Figure 14. Three-millimeter-thick Grade 75 (75 ksi yield) HSLA Steel showing nearly no thickness strain.

Further, using FTI – Forming Suite^{TM}, forming a hat shape begins to show more interesting results. A hat shape has been modeled as the initial forming steps are quite like the initial forming steps in ERW tube making where edge wave tends to begin. And, a three-dimensional model of the hat shape was readily available while modeling the interactions between several tube mill forming stands is not. Note that this modeling software is expecting to form this piece between two dies with the forming direction in the negative Y direction. It is not a complete model of the interactions found during roll forming. It does, however, illustrate the effects of producing this shape. Like the half round shape, different material thicknesses and material yield strengths were modeled.

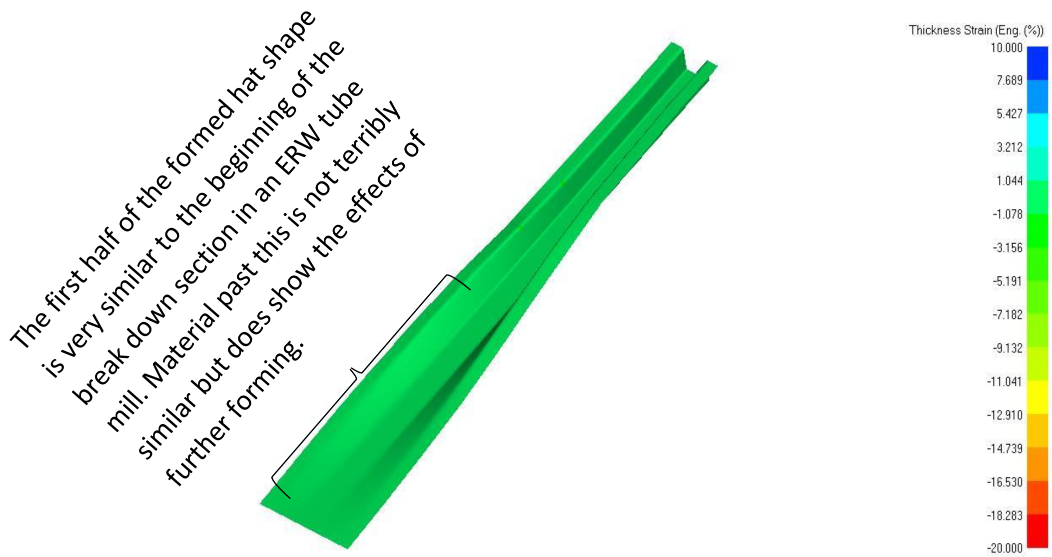

Figure 15. Three-millimeter-thick Grade 50 HSLA Steel showing nearly no thickness strain.

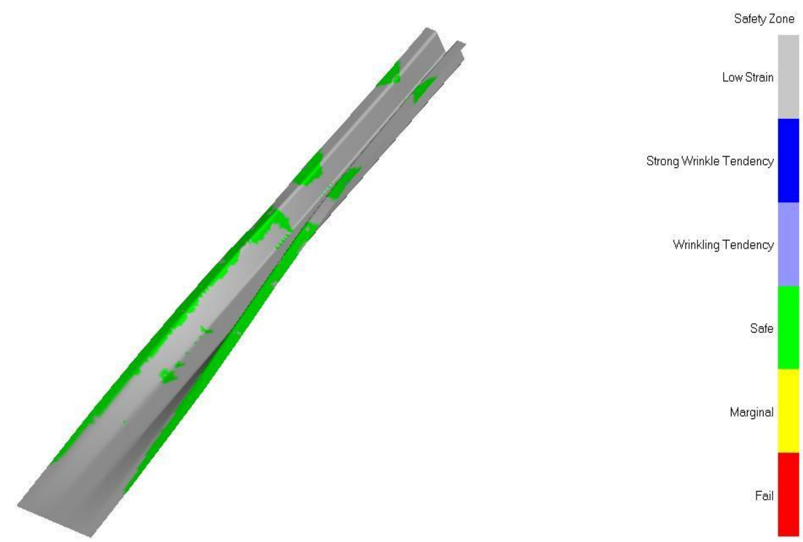

Figure 16. Three-millimeter-thick Grade 50 HSLA Steel showing that the shape should form relatively easily and successfully.

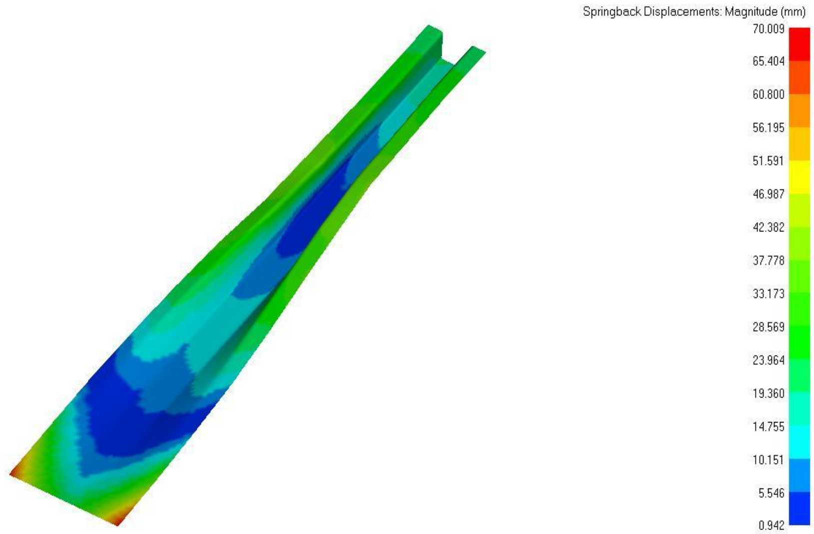

Figure 17. Three-millimeter-thick Grade 50 HSLA Steel indicating that springback will be inconsequential to the forming process.

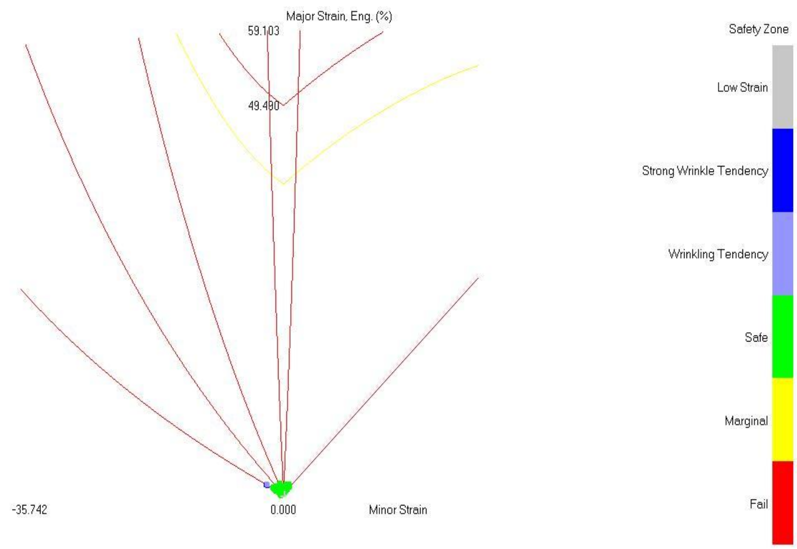

Figure 18. Three-millimeter-thick Grade 50 Steel forming limit diagram indicating the low strains associated with this forming process.

Figures 15 through 18 indicate that forming this hat shape from HSLA Grade 50 steel that is 3 mm thick should not be expected to encounter any major issues.

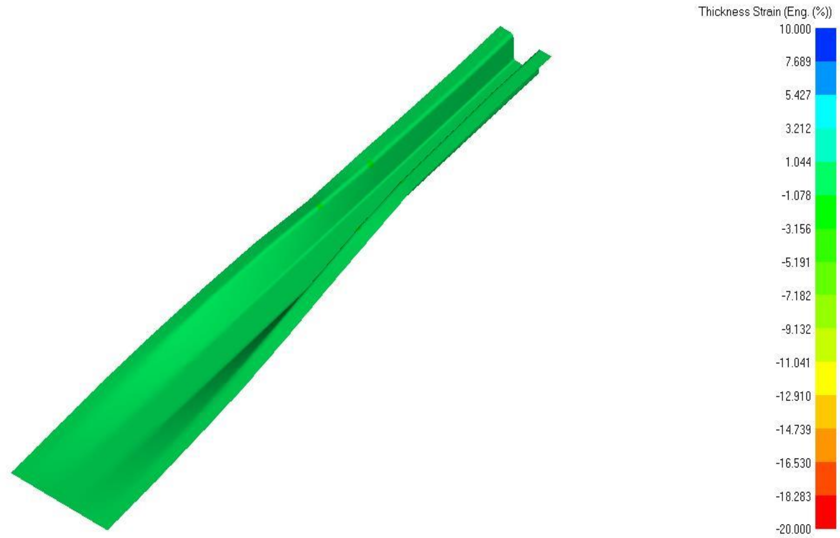

Figure 19. Six-millimeter-thick Grade 50 HSLA Steel showing nearly no thickness strain.

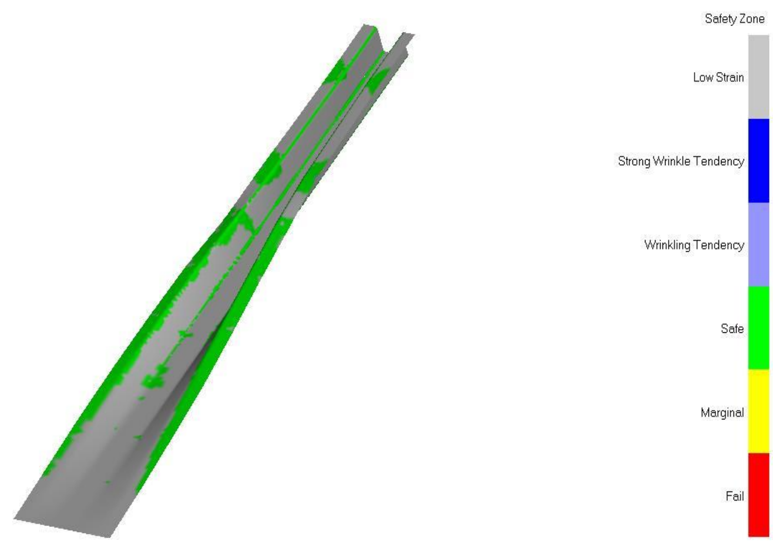

Figure 20. Six-millimeter-thick Grade 50 HSLA Steel showing that the shape should form successfully.

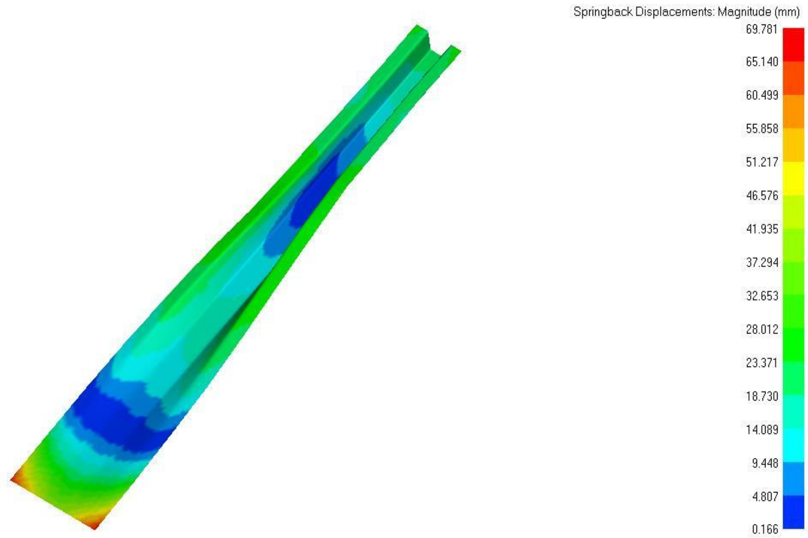

Figure 21. Six-millimeter-thick Grade 50 HSLA Steel indicating that springback will be inconsequential to the forming process.

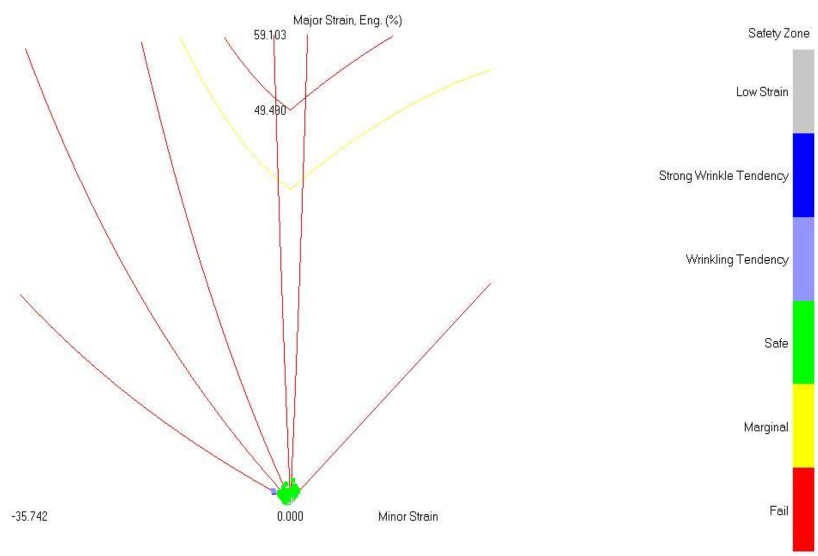

Figure 22. Six-millimeter-thick Grade 50 HSLA Steel forming limit diagram indicating the strains associated with this forming process.

Figures 19 through 22 indicate that forming this hat shape from HSLA Grade 50 steel that is 6 mm thick should not be expected to encounter any major issues. Although minor differences in springback (versus 3mm HSLA Grade 50) are noted, simply changing the thickness of the shape has very little effect in this model.

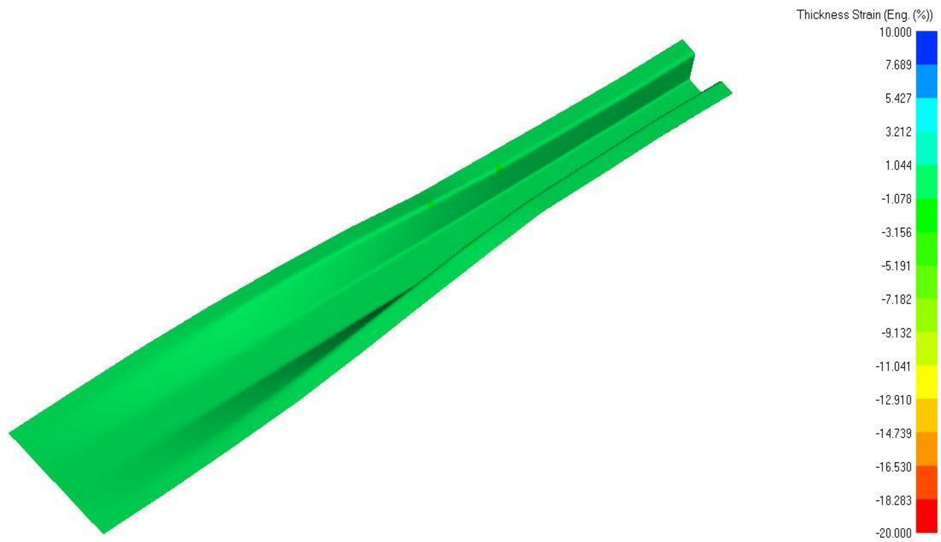

Figure 23. Three-millimeter-thick Grade 75 HSLA Steel showing little thickness strain.

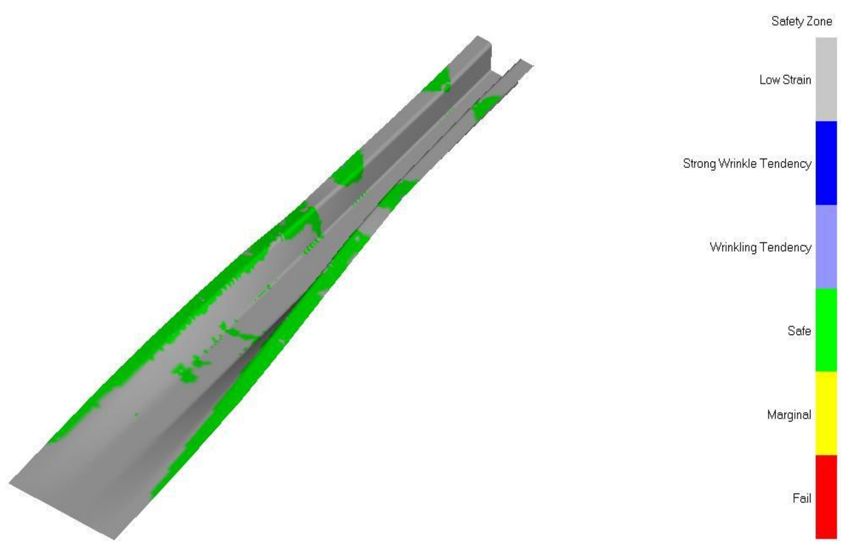

Figure 24. Three-millimeter-thick Grade 75 HSLA Steel showing that the shape should form successfully.

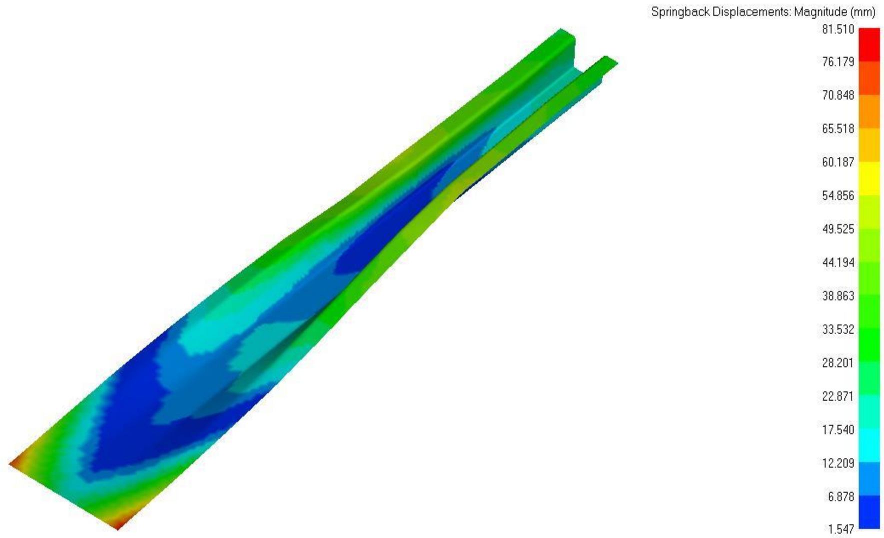

Figure 25. Three-millimeter-thick Grade 75 HSLA Steel indicating that springback will be inconsequential to the forming process.

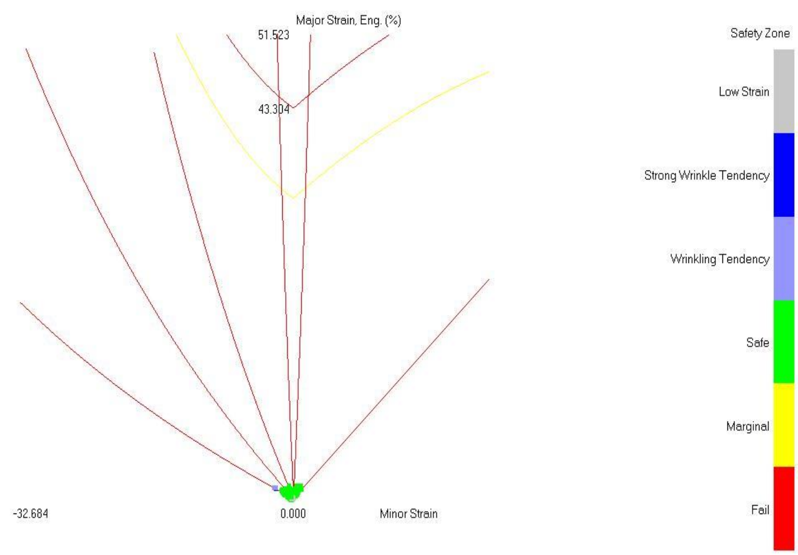

Figure 26. Three-millimeter-thick Grade 75 HSLA Steel forming limit diagram indicating the strains associated with this forming process.

Figures 23 to 26 indicate that forming this hat shape from HSLA Grade 75 steel that is 3 mm thick should not be expected to encounter any major issues. Although minor differences in springback (versus 3mm HSLA Grade 50) are noted, simply changing the strength of steel used in making the shape has very little effect in this model.

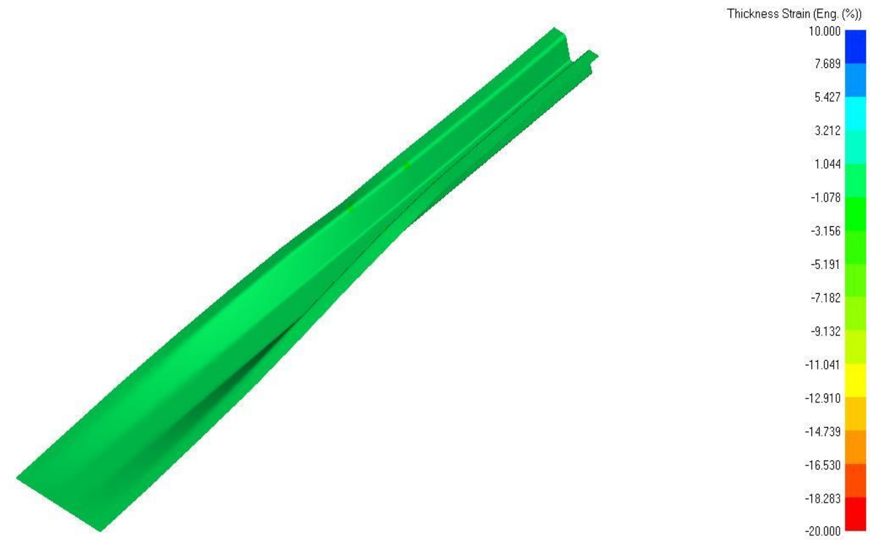

Figure 27. Six-millimeter-thick Grade 75 HSLA Steel showing nearly little strain.

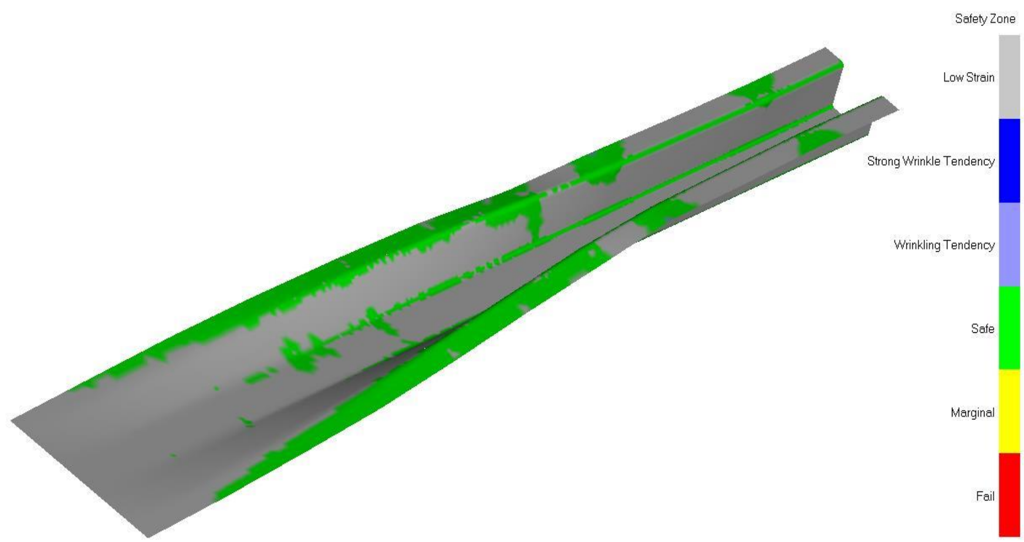

Figure 28. Six-millimeter-thick Grade 75 HSLA Steel showing that the shape should form successfully.

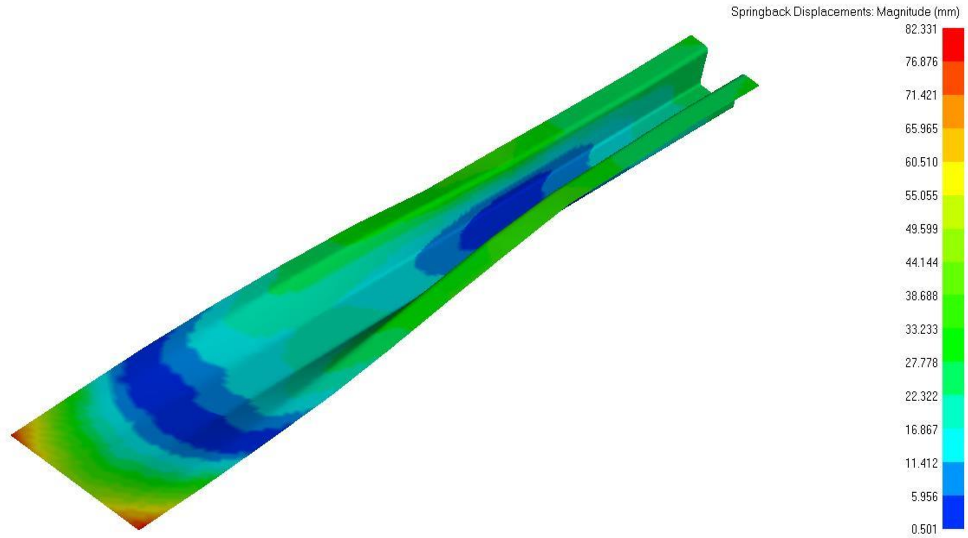

Figure 29. Six-millimeter-thick Grade 75 HSLA Steel indicating that springback will be inconsequential to the forming process.

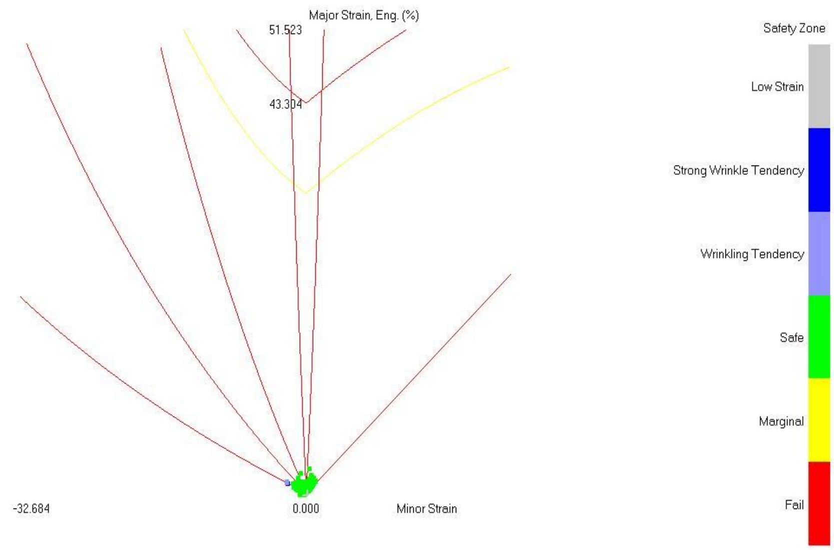

Figure 30. Six-millimeter-thick Grade 75 HSLA Steel forming limit diagram indicating the low strains associated with this forming process.

Figures 27 to 30 indicate that forming this hat shape from HSLA Grade 75 steel that is 6 mm thick should not be expected to encounter any major issues. Although minor differences in springback (versus 3mm HSLA Grade 75) are noted, simply changing the thickness of steel used in making the shape has very little effect in this model.

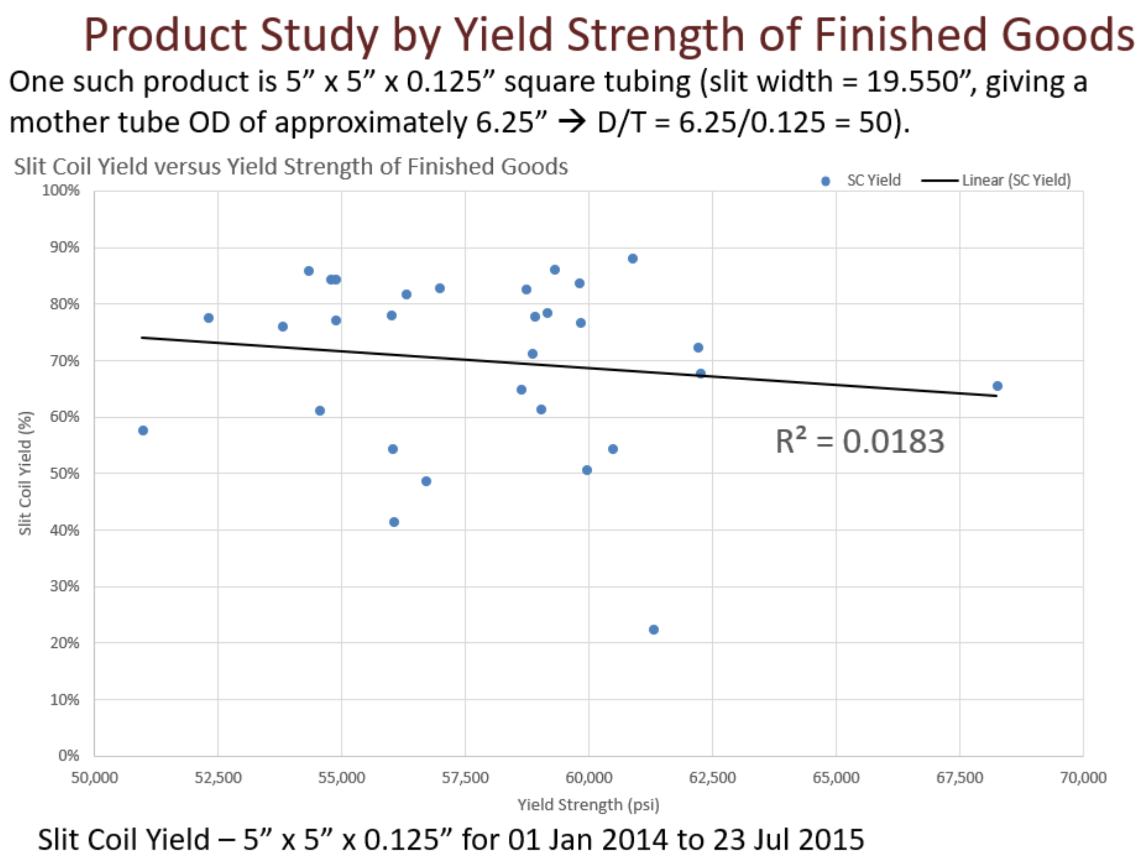

Figure 31. A product study from Southland Tube, Inc. indicating very little to no correlation between poor finished goods yield and material yield strength.

While **Figure 31** specifically shows prime finished goods yield as a function of yield strength, it is important to acknowledge that many other factors contribute to non-prime production. These include surface imperfections, gauge tolerance, lack of straightness and other issues that occur during startups and steady state operation.

EXPERIMENTAL RESULTS AND DISCUSSION

Steel Properties

As the tube forming process relies on symmetric (about the tube mill longitudinal axis) steel properties when these properties (strength, thickness, etc.) vary, localized stresses become non-uniform which leads to non-uniform strains. Flat roll steelmaking is a very well understood process and non-uniformities tend to be rare. The only variation one is likely to see in modern, well-controlled product is gauge variation.

As a steel mill's tooling wears and/or gets damaged, thickness variation across the width of a coil can manifest itself. This can generally be stated in terms of crown and wedge. Crown is an instance where the center of the strip is thicker than the edges and wedge is a condition where one side is thicker than the other.

In any case, the tube mill tooling is expecting uniform cross-sectional thickness. When it sees off-center crown or wedge from either side, it begins to induce a camber in the strip which ultimately results in unexpected deformations including edge wave.

Up to 0.004" differences in thickness across the width of a master coil have been measured and have had no measurable effect on finished goods production. Through production studies done at Southland Tube, it is extraordinarily rare to find thickness variation exceeding 0.004" across the width of a master coil. Thus, finding variation greater than this across the width of a slit coil is nearly impossible.

Mill Tooling

Tube mill tooling is designed to make one cross-sectional size of tubing in across a limited range of thicknesses. For example, the breakdown and fin sections of the tube mill would be designed to manufacture a small range of mother tubes (these mother tubes vary slightly as finished goods thickness changes) that would ultimately be formed into a square tube. The finishing stands merely make the final shape and dimension of the finished good.

This one set of tooling must be able to correctly grasp, pull and form a range of thicknesses and generally cannot be set to "perfectly" form any one thickness. As the tooling diverges from an ideal set up, the setup of the tube mill and material properties become quite important. At some point, perfect steel and perfect setup are still thwarted by poor tool design.

Mill tooling manufacturers and refurbishers use modeling software such as dataM's Copra® to adequately model tooling performance.

Taken all together, changing material thickness and strength appear to only influence springback and this effect appears minor. These thickness and strength values were chosen as they represent a decent cross-section of materials used in the operation. **Figure 12** shows finished goods yield versus yield strength and no real correlation is observed.

Misalignment

Misalignment of the tube mill is heavily influenced by maintenance practices and is generally within the operator's control. Aiding in proper alignment are locating pins that help place the individual tube mill stands in the correct places. And, very little horizontal movement is allowed by the confinement of the tooling within the mill stand housings. These two constraints alone made it very difficult to set up a tube mill as poorly as the initial model requested.

It was possible to, within three mill stands space, set up a condition where the center-to-center offset was measured at 0.92" over a distance of 30" and then calculated to be just short of two degrees (1.76 degrees by the calculation). It should be noted that feeding the strip into this misalignment was very difficult and would therefore be noticeable to the diligent operator at the time of setup.

Once set up, and started, the mill struggled to pull the strip through such a large offset. The strip did move toward the welding rolls and generated an obvious wave (amplitude was measured at 0.8 inches) on the inner radius of curvature on the outward step. Interestingly it generated a somewhat smaller wave (measured at 0.65") on the inner radius and created a series of smaller waves on the outer radius (ranging from 0.13" to 0.25") on the rebound step.

This result is not unexpected. When inducing camber, the mill creates a localized thinning and thickening phenomenon. Constraining these with the mill stands before and after the gross misalignment can lead to the edge wave on the outward step; and, the stretching done (by inducing camber) leaves extra length where none existed before. The extra length is confirmed by the appearance of the edge wave and by noting the edge thickness does not vary more than 0.003" before the gross misalignment and varies as much as 0.010" after.

Many factors contribute to poor quality ultimately manifesting as poor prime yield (not to be confused with yield strength as the two terms often end up being described simply as “yield”). These factors include poorly welded mother tubes (to which improper forming heavily contributes by not allowing good fit and alignment within the weld vee).

The cost of poor quality is of great importance to the tube mill owner. Poor quality can show up in every part of the tube mill. Poor slit edge quality and inefficient slitting (generally found in set up giving to much waste in the cut off edges) tend to lead the way at master coil conversion to slit coil. Transporting slit coil to the tube mill is an opportunity to drop the coil and damage a part of it. Poor forming, improper weld set up, overly aggressive cooling and simple buildup of dirt leading to surface imperfections are all possible within the tube mill. Once the tubes are bundled and ready for shipment, more opportunities exist to drop the tubes. All of this, and more, contributes to poor prime yield.

As an example, one foot of 5” x 5” x 0.125” tube has a calculated weight of 8.15 pounds per foot. The calculation is a misstatement of weight by as much as ten percent as the applicable standards allow for +/- 10% gauge variation. However, it does give us a place to start describing the cost of poor quality. For every foot of this product that is not prime, the initial cost to quality is pretty small (at $500 per ton for steel, each pound is worth $0.25). Not much until you experience quality issues for several thousand feet or while the tube mill is running at 150 to 300 feet per minute. For this product, every foot has a steel cost of just over two dollars. Every 500 feet of poor quality costs this product $1,000 and only considers the loss of the steel and nothing else.

CONCLUSIONS

Tube mill set up is paramount to producing prime quality finished goods. The mill must be correctly set up, the steel strip must be centered on the centerline of the tube mill, the steel should be of sufficient quality and the forming tools must be adequate to the task.

Correct set up is a laborious but well understood process that is well explained in various industry sources such as Thermatool's "Blue Book"[10].

Mill Set Up:

- Mill should be aligned in all three axes. As misalignment increases, the path through the tube mill becomes less straight causing forming troubles that include edge wave.
    - Vertical misalignment is possible when the tube mill is first set up and is very likely an operational issue.
    - Horizontal misalignment is most likely to be seen when locating pins get worn, when bearings near the end of their life and when tooling is assembled. Most of this is governed by proper maintenance and assembly.
    - Longitudinal misalignment is something of a misnomer as the issues found in the longitudinal direction tend to be found in stand

placement and how much work each stand imparts to the skelp. This is largely eradicated by proper tooling design.

- The set up should avoid appreciably reducing the thickness of the steel strip. As strip gauge is reduced, localized strains are increased at the point of reduction which can lead to edge wave.
- The tube mill should make uniform steps during the forming process. If forming stands are doing more, or less, of the forming work than intended in their design, localized strains are adversely affected which can lead to edge wave.
- The forming stands should be “matched”. “Matched” means that each successive stand takes material away fast enough to avoid material pile up but not too fast thereby avoiding spinning on the strip surface which leads to surface imperfections termed roll marks.

Steel strip centered on the longitudinal axis of the tube mill eliminates one source of edge wave formation. When the strip is not centered, as the mill pulls it to the center, it also induces camber in the strip which elongates one side of the strip causing tension on one side and compression on the other.

Similarly, if steel thickness varies across the width of the strip, it can induce camber in the strip leading to the same issue noted above when the strip is not centered. Worth mentioning is variation between steel mill suppliers. Different suppliers can produce a very different master coil based on their standard business. For instance, if a steel mill generally targets automotive customers who place a great demand on formability, that mill’s common steel strip is likely to be quite formable but not achieve great strength.

Conversely, if the steel mill generally supplies to a construction market, their steel strip is likely to be a bit less formable than the previous example but develop greater yield strength on forming. Independently, neither is of considerable importance (except in ordering practice for the tube mill) individually. It is when material from two such suppliers are mixed throughout a production run that issues can manifest themselves.

And, mill tooling should be maintained per the manufacturer’s design and that design should be optimized through process modeling to ensure successful tube forming.

Most deleterious effects can be accounted for and eliminated through scrupulous set up of the tube mill and careful selection of steel suppliers. However, poorly maintained or designed tooling will thwart all set up and supplier selection efforts. When investigating new or problematic finished goods, use of modeling software such as FTI – Forming Suite™ [22] and dataM Copra® [12] becomes invaluable.

FUTURE WORK

- Refine the misalignment model.
    - Model discrete sections using the formed shape of the skelp and applying the simple bending model used herein.
    - Pursue the mathematical expressions described by Toyooka[15].
    - With focus on lateral misalignment, pursue the Finite Element model of Wen, B. and Pick, R.J.[19]
    - Add complexity by increasing the number of stands and/or axes of misalignment
    - Check over multiple mills
    - Observe multiple section and gauge combinations
- Use normalized strip to homogenize internal stresses.
- Use only coil edge slits or centers to limit the amount of shape change encountered.
- Variation in supply of hot-rolled strip (multiple EAF and BOF suppliers)
    - Chemistry (residuals and gasses)
    - Rolling practice (reversing vs continuous)
    - Residual stress
    - Crown, wedge, etc.
    - Initial slab thickness
    - Reheat practice (CSP vs full cool vs semi cool)

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