Lean Innovation for Optomised Tool Change-Over: Validating Product Design Through Practical Procedures

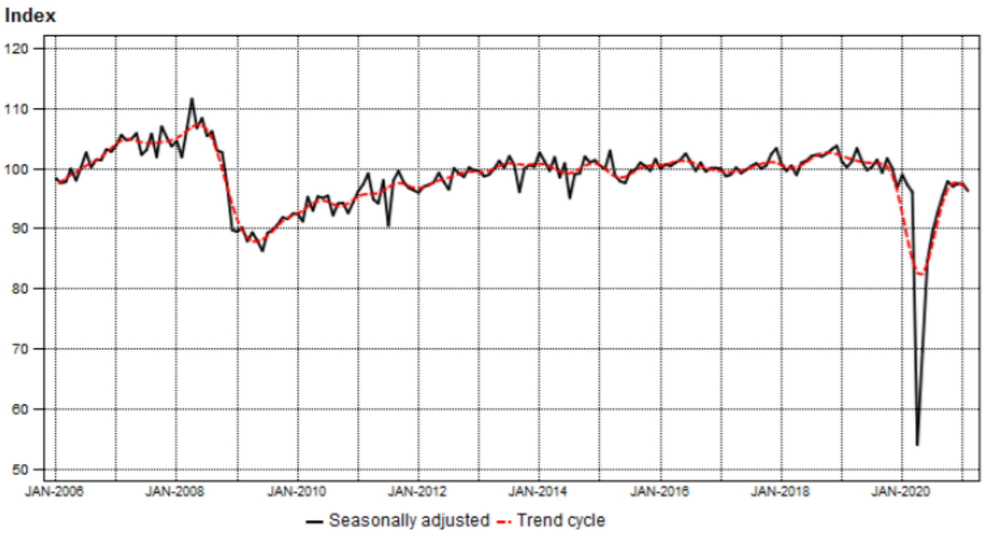
In modern era production, product variety has been recognised as one of the pre-eminent competitive edges for manufacturing organisations to meet customers diverse demands (Nazarian, et al., 2010). In this manner manufacturing organisations must offer product diversity with minimal to zero machine downtime. This research paper considers the cold roll forming (CRF) production process within an automotive accessories manufacturing company. Various diameter tubes are produced at the start of the manufacturing process, drawing considerable amount of attention to the machine downtime due to tool change-over. Lean Innovation characteristics are considered to significantly reduce the machine downtime. An unorthodox forming operation was considered as an alternative to utilising the multiple rollers required for the increment forming of the conventional process. The application of a unique die design is directed at replacing the multiple rollers with a singular tool to address the non-value-added activity of tool change-over and addressing the disadvantages of the conventional CRF process. A prototype machine design was created and utilised to conduct an experimental procedure to inspect the material being formed.

Keywords: *tool change-over, lean innovation, Advanced Manufacturing System (AMS), Flexible Manufacturing System (FMS), lean manufacturing*

Introduction

The entire globe has found itself at the mercy of the Coronavirus disease (COVID-19). Subsequent to the pandemic, economies all over the world are in considerable distress due to disruption in work and operations across all sectors. Focusing on the manufacturing sector, Figure 1 highlights the rapid decrease of the manufacturing industry in South Africa from December 2019 to January 2021. The statistics administers an alarming reality that manufacturing organisations are obligated to operate whilst seriously considering the unforeseen to remain sustainable. The New Growth Theory is an economic concept that emphasises the importance of entrepreneurship, knowledge, innovation, and technology, dismissing the popular belief that economic growth is determined by external uncontrollable forces only (Capolupo, 2009). The implementation of Lean Manufacturing principals and Industry 4.0 technologies can no longer be adopted individually to create a "Smart Factory." They must be married together, coupled with innovative and disruptive ideas to create a golden child, christened "*Lean Innovation*" in order to increase the possibility of sustainability for the forthcoming.

Figure 1. *Statistics of the volume of manufacturing production in South Africa*



Source: Stats SA, Online Lean Innovation defined by Sehested & Sonneberg (Sonnenberg & Sehested, 2011) is about "*getting smart fast*". Lean Innovation is the basis for the development of production systems, separated into three parts of efficiency, ***I)*** *Do the right thing* ***II)*** *Do it right* ***III)*** *Do it better all the time.*

Advancements have been made in the ability to respond to industrial demand with regard to manufacturing flexibility and feasibility. Consequent to the economic volatility more companies have adopted *"Lean principles"* to optimise production rates and maximise profitability by reducing waste. According to Toyota Production System (TPS), waste is regarded as a task or elements that adds no value from the client's perspective. Seven types of wastes are generally identified as (Assaf & Haddad, 2017): ***1)*** *Over-production*

***2)** Inventory **3)** Material transportation **4)** People's movement **5)** Unnecessary operations (over-processing) **6)** Waiting **7)** Product defects.*

CRF is a process that is adopted in a wide range of manufacturing industries which is spread throughout the world. The forming operation is a high-volume manufacturing process that plastically deforms metals by using a series of dies. Hard metals are shaped into the desired geometry at room temperature. Long strips of metal, generally from a coil are sent through several stacks of rollers. The absence of heat results in an obligation for numerous stacks of rollers to add a minuscule amount of forming to the metal strip.

Figure 2. *(a)Material entering, (b) Material exiting the tube mill*

Source: Own work.

Considering the precise and intricate process of cold roll forming, the challenge lies in achieving a tool change-over and setup without compromising on product quality and standards. The proposed solution was to adopt a constant forming ideal by replacing the multiple rollers required to achieve the desired geometry. Where tool change-over and setup is concerned, a singular die is interchanged, providing a significant advantage in achieving tool change-over in a singular minute. This concept is discussed in greater deatil in the Methodology section.

Literature Review

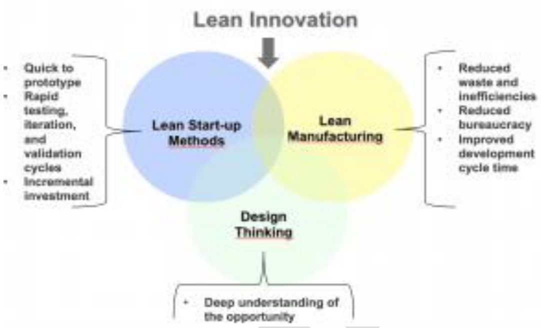
Lean Innovation

Manufacturing companies tend to compete through the optimisation of their products and processes by using conventional methods to gain larger market share. Though these methods prove to be a huge success they do not equip organisations with the necessary tools to adapt to the volatility of industrial markets. Innovation is an essential characteristic that allows organisations to operate in an advanced environment that may aid with sustainability through the unforeseen. Claus and Henrik define Lean Innovation as working efficiently with knowledge and getting smart fast (Sehested & Sonnenberg, 2010). Lean Innovation is a combination of three main methodologies, as explained by Tucker Marion (Tucker, 2015):

1. The ability to identify new opportunities through ***design thinking***.
2. The ability to ***quickly*** and with few resources, develop, prototype, learn, validate and improve solutions that may leverage an opportunity discovered during the design thinking process.
3. ***Lean processes,*** applying lean processes to reduce waste and continuous improvement to existing methods.

Figure 4 illustrates the various elements contributing to a Lean Innovation system and breaks the elements down into sub elements.

Figure 3. *Elements of Lean Innovation*



Source: Online.

Conventional CRF mill design process

Since the early 1800’s, roll forming has evolved into a well-established process for the forming of components of uniform cross-sections from sheet metal. CRF is a continuous bending exercise, where the bending occurs incrementally in multiple forming steps, from an undeformed strip to a finished profile. The forming process is highly sophisticated, as forming does not occur due to the forming stands (die/tools) only but occurs between the stands as well (where no tooling is present). Multiple factors influence a roll forming design process to achieve a desired geometry. Concerning the tool design, the designer must first determine how many forming steps are necessary. The required steps are dependent on the shape of the cross-section, thickness of material, material properties and tolerance (Lindgren, 2007). The amount of forming steps should be kept to a minimum, as this will aid with reduced investment costs to the design. The minimum distance between two deformation roller sets are limited to a minimum deformation work spent on longitudinal plastic deformation (Smith, et al., 1984), given by:

$$L = \sqrt{\frac{8.a^3.\Delta\Theta}{3.t}} \qquad (2.3.1)$$

Where,
L, Distance between two deformation sets, mm
a, Flange length, mm
$\Delta\Theta$, Bending angle, degrees
t, Thickness of the material, mm

Figure 4. *Adjustable deformation sets/rollers*

Source: Own work

Halmos (Halmos, 2006) details the step by step procedure to designing a CRF mill. The following highlights the basics of a CRF design process;

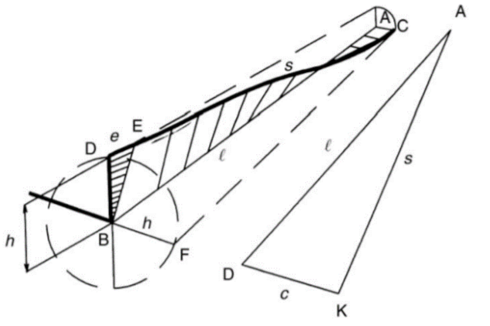
- Product cross-section: The cross-section of a product is the most significant factor in roll design. Consider Figure 5 where;
  ℓ, length of the bend line traveling from point A to B.
  h, strip edge travels in a helical pattern for the length and upward by a height of the leg.
  s, overall length of the travel.
  c, arc length from point F to D.

The length of the material travel is given as;

$$s = \sqrt{\ell^2 + c^2} \qquad (2.3.2)$$

$$s = \sqrt{\ell^2 + \frac{h^2}{4}\,\pi^2}$$

Figure 5. *Theoretical path of metal strip during forming*



Source: Journal paper (Soyaslan, 2018)

- Orientation of forming: Prior to calculating the number of passes required for forming, the orientation of the finished section must be determined. Given the simplicity of the tube geometry and manufacturing nature of ERW tubes, welding generally occurs at the top of the formed section, thus forming should ideally occur symmetrically. The simpler the geometry of product, the fewer the required number of passes.
- Number of passes: Numerous attempts have been made to introduce science into roll forming. Halmos, has developed an empirical formula to serve as a guideline to determine the number of passes required, this serves as a mere guideline, simulation and software packages tend to be more accurate and aid in the design process:

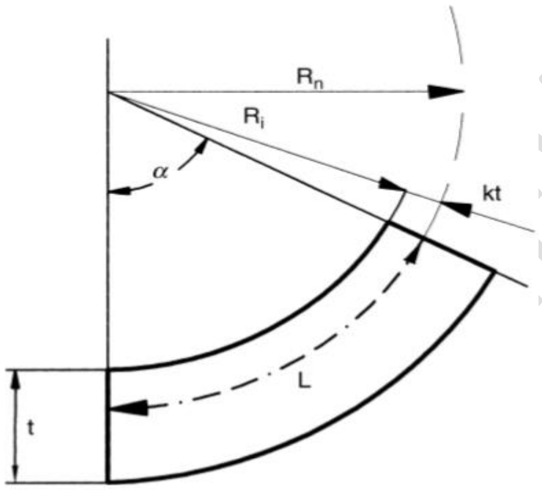
$$n = \left[3.16h^{0.8} + \frac{0.05}{t^{0.87}} + \frac{\alpha}{90}\right]\left[\frac{Y^{2.1}}{40U}\right]^{0.15} s(1 + 0.5z) + e + f + 5zs \qquad (2.3.3)$$

Where,
n, is the estimated number of passes
h, is the maximum height of the section
t, is the material thickness
α, is the sum of the formed angles on one side of the guide plane
Y, is the yield strength (MPa)
U, is the ultimate tensile strength (MPa)
z, is the pre-punched hole/notch and strip continuity factor
s, is the shape factor

e, is the number of extra passes for other operations
f, is the tolerance factor

- Strip width: To accurately determine the strip width of a coil the final cross-section must be divided into straight and curved elements. For the purpose of the strip width calculation it is assumed that the length of the straight elements does not change during the forming process. During forming, it is assumed that the theoretical neutral axis of the bent element moves from half of the thickness location towards the inside radius. Consider Figure 6 where;
  L, length of the curved element.
  t, thickness of the material.
  R_N, neutral axis radius.
  R_i, inside radius.
  k, “k” factor (Determined from tables and theoretical equations).

Figure 6. *Length of curved element*



Source 1: Book

$$L = \frac{\pi}{180}(R_i + kt)\ \alpha \qquad (2.3.4)$$

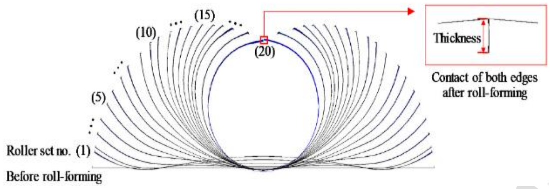
2.3 Finite Element Modelling (FEM) and Finite Element Analysis applied to the CRF process

The CRF environment has notoriously been known for demanding high levels of labour and experience from operators. These demands become highly unproductive when it comes to troubleshooting, problem solving and costly (given the lengthy change-over times).

Presently, there are numerous computer programmes available that can support the overall requirements (design and problem solving) of the CRF environment. FEM is a numerical approach to determine approximate solutions to boundary value problems. The application of FEM to simulate and analyse sheet metal forming processes has become more common over the years, however this is not necessarily the case in CRF. The programs and software are simplified formulas, unfortunately the conclusions are limited due to the complex geometry of the deformed strip and the simplifications in their design rules (Lindgren, 2005). Significant strides have been taken into developing software for FEA, some of the packages are COPRA, MARC/ MENTAT, ABAQUS and PROFILE, to name a few. Further details of the software operation can be found in (Lindgren, 2005).

The initial design process of a roll forming mill is generally based on a "*Flower pattern diagram*." This diagram consists of the superimposition of the cross-section of the strip at each forming stand on a single plane, the diagram is a 2D representation of the 3D process. Figure 6 below represents a typical flower diagram for the forming of a round tube;

Figure 7. *Flower diagram of a circular tube during forming*



Source: Journal paper

The representation of the flower diagram on the various FEM packages is an indication of the advantages of simulation software packages. Errors and possible defects can be picked up initially instead of downstream where changes could prove to be time consuming and costly.

Methodology

Organisation Background and the Production Details

The company under investigation is one of the premium automotive accessory manufacturers in South Africa. The products manufactured by the organisation include, nudge bars, styling bars, sports bars (used on light motor vehicles like SUV's) and bull bars (used on trucks). Though the variety of products have their unique purpose and function on a vehicle, they all have one thing in common, they require a circular or oval stainless steel or mild steel tube for a complete product. The different sized tubes manufactured are:

- 76.2mm, round and oval.
- 63.5mm, round and oval.
- 50.8mm, round and oval.
- 38.1mm, round and oval.

Provided, the tube manufacturing sector is not the primary focus of the business, optimising the manufacturing process has been neglected. The organisation has two tube mills, tube mill one and tube mill two, of which will be referred to TM1 and TM2 respectively. TM1 is approximately 15 years old and TM2 approximately 10 years old. Both sets of machinery have significant wear and tear, resulting in additional inconsistencies.

Change-over and Setup Process

Depending on the diameter of the tube to be manufactured, specific components and dies are selected, transported and loaded by forklifts, then assembled and fastened by experienced individuals. A case study regarding tool change-over, conducted over one month for TM2 is highlighted in Table 1. The average change-over for the month is 519 minutes and average setup scrap is 12.1m.

Table 1. *Details of change-over conducted in a month*

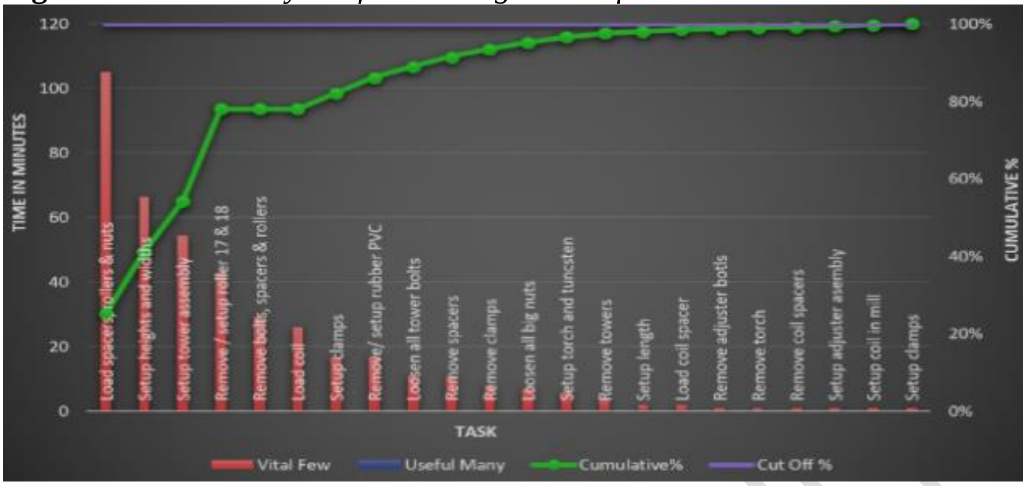
Change-over	Time required	Diameter change	Scrap
1	507 min	38.1 to 50.8	4.4m
2	576 min	50.8 to 76.2	12.8m
3	403 min	63.5 to 50.8	14.7m
4	588 min	50.8 to 76.2	19.5m

Source: Own work

The largest contributor to the change-over downtime is concerning tooling (rollers, spacers and fasteners), contributing 24% of the total change-over, as seen in Figure 9. The nature of the change-over can be conducted as a project. A project is defined as a temporary endeavour that is conducted to create a unique product, service or result (Stojčetović, et al., 2015). In project management numerous quality tools are used, a Pareto analysis is one of them. A Pareto analysis is a statistical technique used in decision making for the selection of a limited number of tasks that produce a significant overall effect (Talib, et al., 2010).

From Figure 10, it is evident that the tasks involving the tooling to manufacture a specific diameter tube consumes the most time. This proves to be the pricey area of the overall change-over. J.M Juran applied the 80:20 rule to quality control and realised that 80 percent of problems stem from 20 percent of the possible causes (Juran, 1998). Juran stated that the main point is to focus on the vital few problems instead of the trivial many, to make the most significant improvements to quality.

Figure 8. *Pareto analysis of tool change-over of the tube mill*



Source 2: Own work

Theoretically, if the specific components to (rollers, spacers and fasteners) manufacture a tube can be changed in a singular minute (anything less than 10 minutes), the overall change-over has the potential to be completed in 331 minutes. Though 331 minutes is a considerable time to lose to production, achieving this target will be a huge achievement in cost saving. This justifies the research into the single forming die design and concept discussed in further detail in section 3.3.

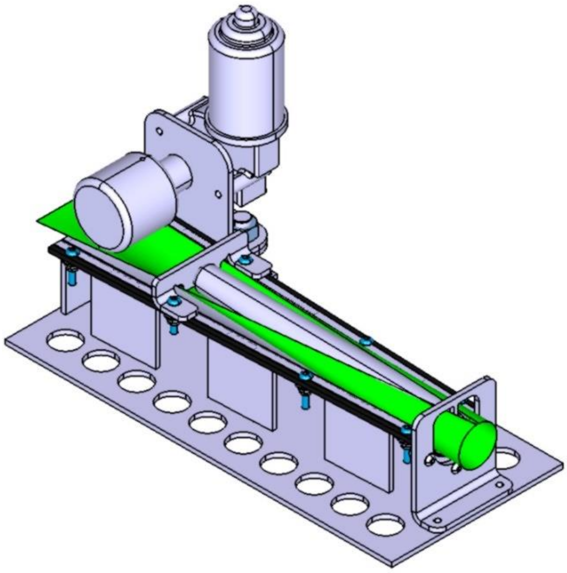
Forming Die Development

The theory behind developing a machine design that significantly reduces tool change-over within the CRF process, through Lean Innovation was addressing the number of tools that are used for forming. For the two tube mills that are used at the organisation, each tube mill requires 22 rollers to be interchanged and adjusted individually and manually for the completion of a successful tool change-over.

> **Concept 1:** Concept 1 considers the notion of *forcing* the material through the forming die. In theory the knurled roller should grip onto the top face of the material, forcing the bottom face onto the die whilst projecting the material forward, inducing forming. From Figure 11, the material in green (for illustration purposes only) is kept in contact with the tool by using a mandrel. The mandrel is geometrically specific to the tube being formed. This will also have to be changed when conducting a tool change-over. As the material is moved from the entrance of the die, forming gradually occurs until a perfectly round tube is formed at the exit. For the purpose of this research the welding process is omitted. However, a perfect weld gap at top of the formed tube needs to be achieved for the concept to be deemed successful.

Upon the prototype trial run the theory of using a single roller to force the material through the die will not be considered as a solution, as this theory was proven unsuccessful. This will be discussed in more detail later on in the paper.

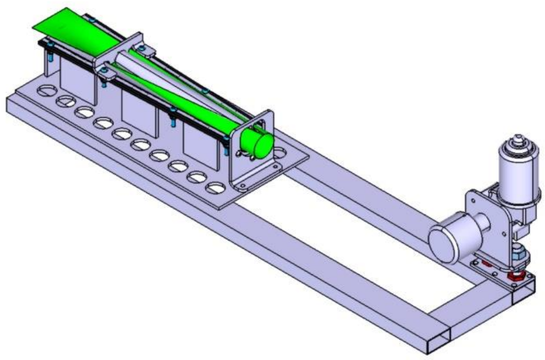
Figure 9. *Isometric view of Concept 1*



Source 3: Own work

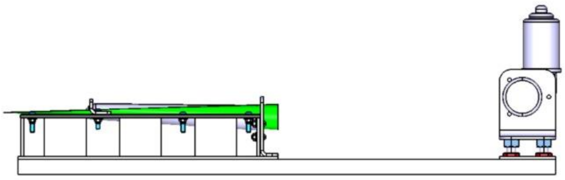
Concept 2: The idea of having a pulling force was considered as opposed to a pushing force in Concept 1. The motor, roller arrangement was removed from the entrance of the machine and assembled at the exit end, as seen in Figure’s 10, 11 and 12. As with Concept 1, the knurled roller will be used to grip the material whilst rotating about its own axis. The roller will no longer be used for forcing the material onto the die, but be utilised as a pulling device. As the roller rotates about its own axis the material is pulled forward through the die. This is explained in further detail later on.

Figure 10. *Isometric view of Concept 2*



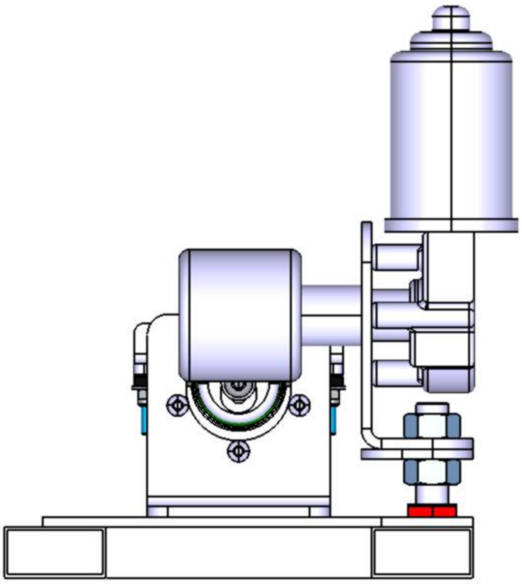
Source 4: Own work

Figure 11. *Left side view of Concept 2*



Source 5: Own work

Figure 12. *Front View (Exit) of Concept 2*



Source 6: Own work

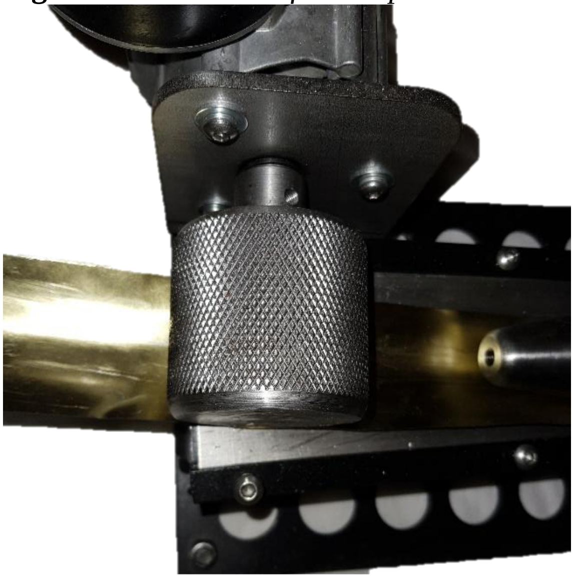
Results

Details of the prototype machine design arrangement are highlighted in Table 2.

Prototype Trial Run 1: Concept 1

This trial run considered Concept 1, as previously discussed, this was not a success. Though the contact between the material and roller was sufficient the material was not able to overcome the fictional force generated by the contact of the material and the sleeve. Figure 15 highlights the trial run conducted. As indicated by the image, the material was not able to move past the roller. The material was fed into the machine manually and forced past the roller by hand. The material did not move beyond this point when dependant on the motor.

Figure 13. *Trial run of Concept 1*



Source 7: Own work

Table 2. *Details and functionality of the prototype components*

Component	Details	Function
Die/ sleeve	400mm x 3mm (thickness) 304SS. Sleeve is flat faced at entry of the material and gradually transforms along its length into a semicircle of 30mm exit of the material.	Used to house and form the material.
Mandrel	Material, EN8 mild steel. At entry the part is tapered, and changes to the geometry of the die.	Used to keep the material in contact with the sleeve.
Motor	DC motor. 70rpm at 12V.	Used to drive the roller.
Roller	The roller is not geometrically specific with a knurled finish.	Used to move the material through the sleeve.
Supports	Die; 5mm thick mild steel powder coated. Mandrel; 5mm thick 409ss.	Keeps the parts in their desired positions.
Material	Shimstock brass, 0.25mm thick. Material was cut at 78mm width.	Used to confirm the machine design.

Source 8: Own work

Prototype Trial Run 2: Concept 2

Concept 2 requires the material to be cut a little differently to use the roller arrangement at the exit end of the machine. A thinner strip of material is attached to the piece of material that will be formed, as seen in Figure 14. The thin strip is attached to the roller, as the roller rotates the strip will coil around the roller, resulting in the material being pulled forward through the die.

Figure 14. *Material used for Concept 2*

Source 9: Own work

Figure 15. *Prototype machine arrangement*

Source 10: Own work

Figure 16. *Material being formed*

Source 11: Own work

Figure 17. *Material at exit*

Source 12: Own work

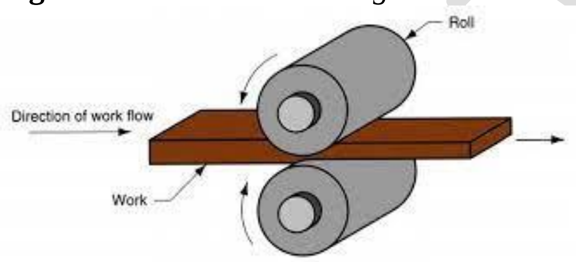
Figure 15 highlights the prototype arrangement. Due to the nature of the material being used, the material did not grip onto the roller as intended. The material continuously slipped, and intern did not pull the material straight through the die. Figure 16 shows the material being wrinkled as it passes the mandrel. This will cause substantial defects in the material and increase the scrap rate. Figure 17 shows the material upon exit of the die, the material is not being pulled directly through the centre of the die. Unfortunately Concept 2 was not a success aswell. Though Concept 2 proved to be unsuccessful, improvements to the concept will be considered and discussed in the Recommendations section.

Discussion and Recommendations

Both concept trial runs are deemed unsuccessful. Though unsuccessful, the unique die design is not proven to be a failure. An efficient method to gripping the material and pulling it through the die needs to be developed. It was noted that the material is not being pulled straight through the die. This is of serious concern as a perfect weld gap is required at the top of the formed tube for the machine design to be regarded successful. As with the existing cold roll forming process, a set of guide rollers will have to be adopted into the machine design. This will not affect the change-over process, the guide rollers will accommodate all diameters.

For the development of an improved machine design, two rollers will be used to pull the material through the die. The roller arrangement will rotate opposing each other resulting in the material being pulled forward, as seen in Figure 16.

Figure 18. *Feed roller arrangement*



Source 13: Online

Conclusion

The continuous forming die concept is yet to be proved concerning the impact on tool change-over and the ability to produce defect free useable tubes. Extensive research still needs to go into the concept. The recommendations need to be implemented into the machine design and more trial runs need to be conducted to verify the findings.

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