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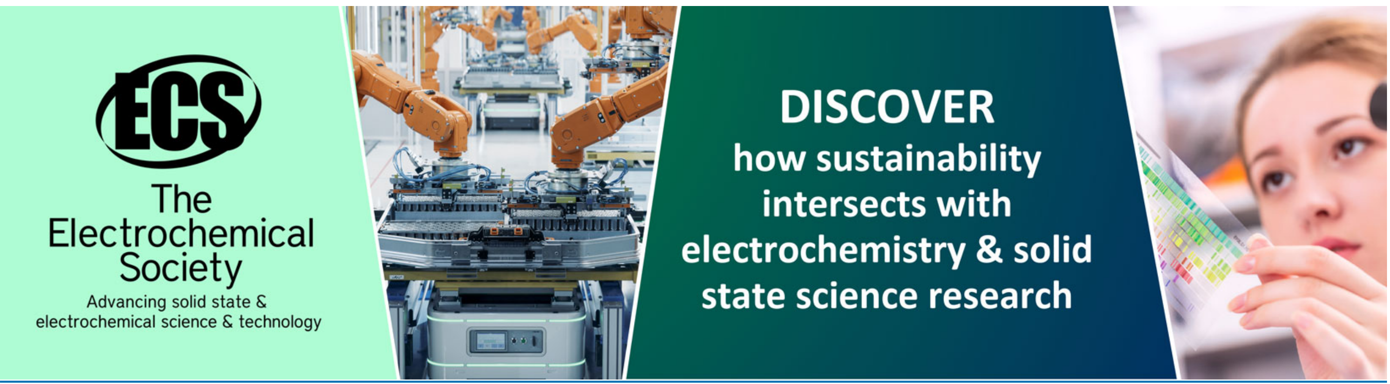

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An Investigation on Square Tube Forming using a Reuleaux triangle

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Abstract. Currently the standard for forming tube is to use a variety of shaped mandrels and hydrostatic pressures. Tube forming is the expansion of a circular cross-sectional area into a variety of different shapes. This paper is focused on square tube forming. Traditionally to create a tube with a square cross-section area, a square mandrel must pass through the circular tube in small increments until the circular cross-sectional is completely transformed into a square cross-section. A novel process named Reuleaux forming to flare the tube in to a square section is introduced and the results were compared with conventional forming. In this new process, a triangular shaped bit flares circular cross-sectional tubes to square tube. While experimenting with the Reuleaux triangular bit, the force required to form the tube, profile generated and thickness distribution were analyzed. Furthermore, the effect of friction and punch speed on deformation was studied. It was found that much lower forces were required to form the shape using the Reuleaux triangle as compared to conventional forming. It was also observed that the friction and speed does not affect much during the new process.

1. Introduction

Current tube forming methods use a square mandrel or hydrostatic pressure to expand a circular cross-sectional area into a square, and have been used for many decades [1]. The dimensions of the tubes are dominant within the width and the length, when compared to the thickness, thus tube forming is considered a plain stress analysis [2]. Currently, square tube forming requires a large amount of energy in order to deform the tubes to the proper shape. To form a tube with a square mandrel, the square mandrel must first be attached to a large press. Next lubrication is added to both the circular tube and the mandrel. Finally, the square mandrel is pressed through the circular tube causing the cross-sectional area to deform into the shape of a square. Different shapes can be used to create the desired cross-sectional shapes [3].

Tubes are used largely for fluid flow or within engine structural supports [2]. Square tubes are popular among engine supports due to the higher yield and tensile strength compared to circular cross-sections. The square cross-sectional area also allow the tube to experience higher temperature, pressures, and destructive elements [4].

Reuleaux triangles are an equilateral triangle in which the edges of the triangle are rounded. To create a Reuleaux triangle an equilateral triangle must be drawn first. Each edge of the Reuleaux triangle composes of circular arcs with the center at on vertex passing through the other two vertices [2, 5]. The dimensions and more details procedure to create the Reuleaux triangular bit are explained in [2, 5].

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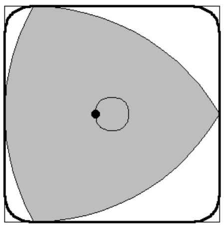

Figure 1. Reuleaux triangle rotation and translation to create square

Currently the Reuleaux triangle is commonly used to drill square shapes through a variety of material [6]. In order for the Reuleaux drill bit to operate properly both, the rotation along the longitudinal axis and planar motion perpendicular to the longitudinal axis of the bit, is required [6]. The use of Reuleaux triangular bits for lathes can save time while being more cost effective than cutting square holes into material [7]. Reuleaux triangles are also used in rotary internal combustion engines, instead of pistons which are found in more common vehicle engines [8].

For every planar rotation that the Reuleaux bit experiences, the entire bit would have rotated nearly three full cycles. The initial idea of using a Reuleaux triangle to drill square holes was developed in 1978 by Morrel et al [2]. Similar to the method of drilling square holes in a material, a Reuleaux triangle can also be used to deform circular tubes into squares. The purpose of this experiment is to test different strain and frictional effects due to the Reuleaux triangle tube forming and compare them to conventional mandrel tube forming. Today little information is known on the effects of interface friction on material flow, damage, and strain path on location of fracture in conventional tube forming [3, 9-11]. The first experiments presented are to investigate the strain rate, and frictional effects on conventional tube forming. Tubes were tested at different speeds with and without lubrication to investigate the formability. The results are compared and presented.

2. Material and Methodology

2.1 Tensile Test

Dog Bone samples were cut out of the 1018 steel tubes. These experiments then were conducted within a MTS machine. The strain rate was set at 5 mm/min. Material properties such as the yield stress, ultimate tensile stress, and the modulus of elasticity were then calculated.

2.2. Conventional Square Tube forming

The test samples were first deformed conventionally using a tapered square mandrel. Each samples had the same height, inner diameter and wall thickness. The default axial speed for the first test was 5 mm/min. The samples were placed on the Tinius-Olson machine, centered axially with the tapered square mandrel. At the default axial speed of 5 mm/min two different experiments were performed. The first was the mandrel and tubes without lubrication, and the second was with the application of Ford Motorcraft PTFE lubrication. Next, the axial speeds were set to 2.5 mm/min and 7.5 mm/min. Both of these experiments were conducted with Ford Motorcraft PTFE lubrication, and were conducted in order to investigate strain rate effects of conventional tube forming. All of the conventional experiments were conducted until the tube experienced failure. Figure 2 demonstrates the process used for conventional tube forming.

Figure 2. Conventional tube forming using a square tapered mandrel.

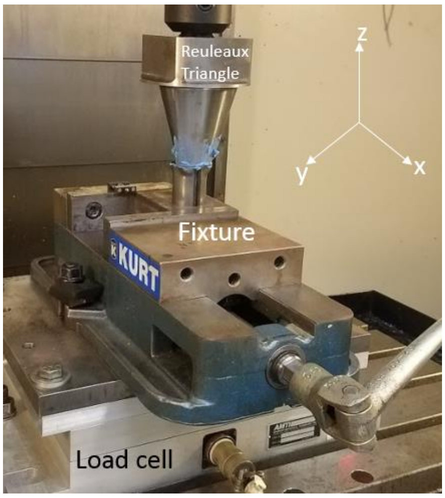

Figure 3. Tube forming using a Reuleaux triangular bit.

2.3. Reuleaux Triangular Tube forming

Four different experiments were conducted using Reuleaux tube forming. For all four experiments, the Reuleaux bit was first placed within a Haas CNC machine. On the bed of the Haas CNC a load cell and a clamp were placed to hold the tubes in place and record forces acting on the tube (Figure 3). The Reuleaux triangle for all of the experiments was rotating at a speed of 20 rpm, but had varying axial speeds. The total distance the Reuleaux triangular bit traveled axially was 1.25 inches, to prevent any contact between the bit and the clamp. The first axial speed tested was at 5.667 mm/min, and this was conducted with and without lubrication to compare the effect that friction has on Reuleaux forming. The next experiment was at 2.33 mm/min and 8 mm/min, both of these experiments were conducted with lubrication and were to investigate strain rate effect.

2.4. Thickness Measurements

After all the tubes were deformed, the wall thickness of the deformed tubes was measured. The measurement started at the corners of the tubes where fracture had occurred. Measurements were taken in 5 mm intervals until the center of the tube walls was reached. The positions of the measurements can be observed in Figure 4.

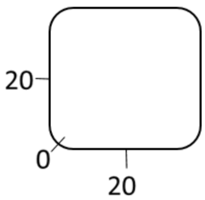

Figure 4 The location of measurments taken on the deformed square cross-sections.

3. Results and Discussion

3.1. Tensile Test

The tested material stress-strain curve is shown in Figure 5. Material properties such as yield stress, ultimate tensile stress, modulus of elasticity, strength coefficient, and strain hardening exponent were calculated, and can be observed in Table 1. The modulus of elasticity was calculated from the slope resulting from 0.2 to 0.6% strain. This location was selected because the slope contained the least amount

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of noise, which resulted in a more accurate modulus of elasticity. The strength coefficient and the hardening exponent were calculated using Holloman Ludwik's law from the true stress stain curve.

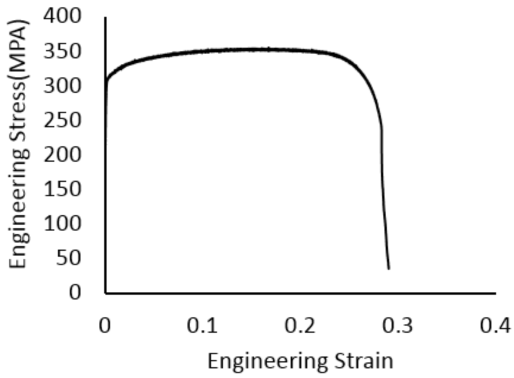

Figure 5. Engineering Stress Strain Curve of the 1018 steel

Table 1 Mechanical properties for 1018 Steel

Yield strength (MPa)	Tensile Strength (MPa)	Young's Modules (GPa)	K (MPa)	n
285	340	201.68	543	0.15

3.2 Conventional Tube forming

For the first experiment, three tubes were tested at a speed of 5 mm/min with Ford Motorcraft PTFE lubrication. The experiment was performed until the tube experienced a fracture. The max force experience from the lubrication test was around 25 kN. For the second experiment, three tubes were tested at a speed of 5 mm/min without Ford Motorcraft PTFE lubrication. The max force experience from the dry experiment was 43 kN. The experiment without lubrication required 72% more force than the lubrication experiment (Figure 6). The increase in force required to deform the tube indicates that the frictional forces play a major role in conventional tube forming.

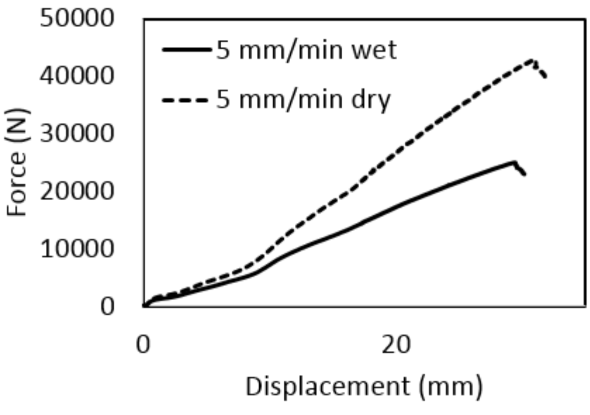

Figure 6. Frictional effect on conventional tube forming

The second set of conventional tube forming experiments included three tubes tested with an axial speed of 2.5, 5 and 8 mm/min with Ford Motorcraft PTFE lubrication. The max force experienced during the lubrication test for all speeds was around 25 kN. The formability achieved in 2.5 mm/min was more than 5mm/min tan 7.5 mm/min (Figure 7). This indicates that the strain rate effects during conventional tube forming are minimum.

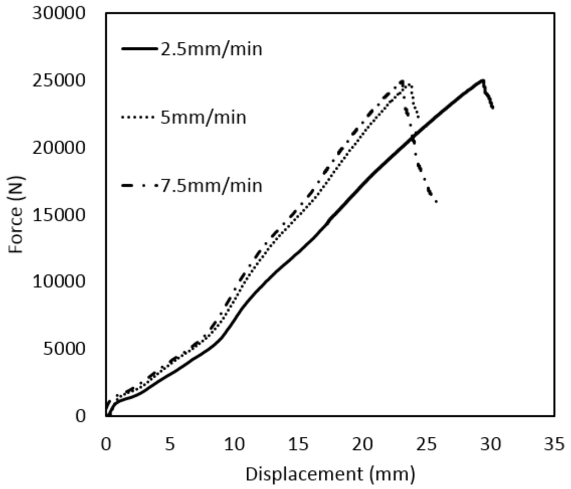

Figure 7. Strain rate effect on conventional tube forming

3.3 Reuleaux Triangle Tube Forming

The first Reuleaux tube forming experiment used Ford Motorcraft PTFE lubrication at an axial speed of 5.33 mm/min. The force required in the X, Y, Z-directions can be observed in Figure 8. The max force in the X, Y and Z-direction were 408.4 N, 374.8 N, and 498.6 N, respectively. The forces were very similar in X and Y-direction as that was the plane of forming. Z-direction force is little higher which was flaring the unflared tube section, however X and Y-direction force were supporting as well as shaping the tube square profile.

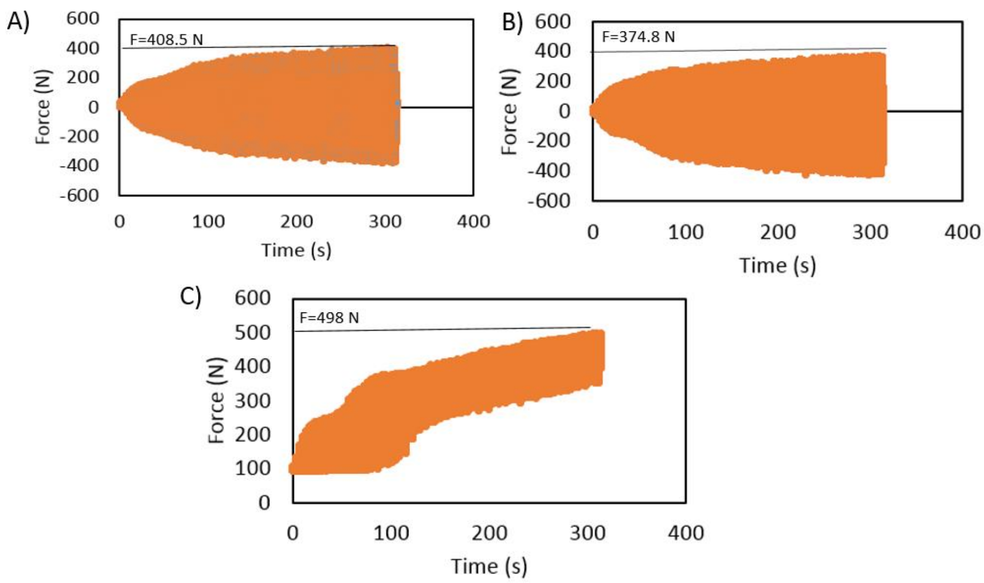

Figure 8. Reuleaux forming with lubrication with Z speed of 5.33mm/min A) X, B) Y, and C) Z directions

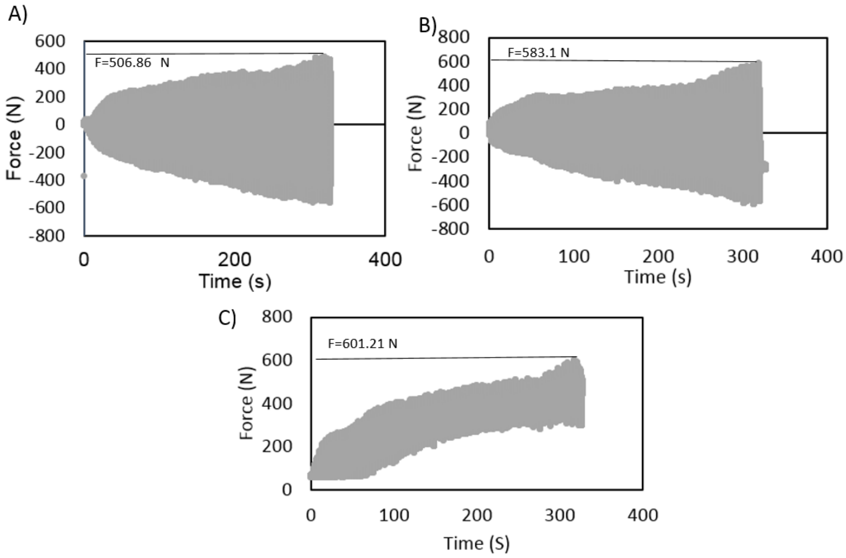

Figure 9. Reuleaux forming without lubrication with Z speed of 5.33mm/min A) X, B) Y, and C) Z directions

The second set of experiments were conducted at 5.33 mm/min strain rate without lubrication. The force required in the X, Y, Z-directions can be seen in Figure 9. The max force in the X, Y and Z-direction are around 506.8 N, 583.1 N, and 601.2 N.

The max force experience in the X-direction at a strain rate of 2.67 mm/min was 394.1 N. While the max force in the Y-direction was 364.1 N, and finally the max force in the Z-direction was 454.133 N. The max force recorded for the 5.33 mm/min strain rate experiment in the Z-direction was 498.62 N which was 9.5% larger than the 2.67 mm/min strain rate. The max force experienced by the 2.67 mm/min strain rate experiment can be observed in Figure 10.

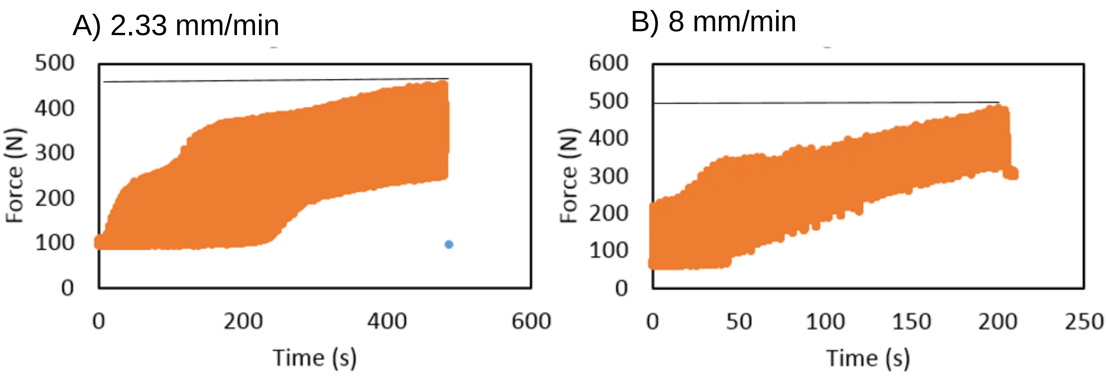

Figure 10. The strain effect from Reuleaux tube forming

The max force experience in the X-direction at a strain rate of 8 mm/min is 368.1N.While the max force in the Y-direction was 421.1 N. The max speed in the Z-direction was 481.4 N. The max force required by the 5.33 mm/min strain rate experiment in the Z-direction was 498.6 N, and had a force 3.3% larger than the 8 mm/min strain rate. The max force experienced by the 8 mm/min strain rate experiment can also be observed in Figure 10.

3.4 Comparison

The max force experienced by the conventional 5mm/min wet and dry tube forming was 25 kN, and 43 kN (Figure 11). As mentioned earlier the percent difference between force was 72%. Such a large percent difference indicates that the frictional forces have a large effect on traditional mandrel square tube forming. The maximum force experienced in the tube at 5.33 mm/min Reuleaux triangle wet and dry in the Z-direction test are 498.6 and 601.N. The percent difference between the two experiments are only 17%. This indicates that the frictional effect on tube forming using a Reuleaux triangle bit is far less than the frictional effect on conventional mandrel tube forming.

The maximum force experienced by the conventional 2.5 mm/min, 5mm/min, and 7.5mm/min strain rates with lubrication are very similar (Figure 11 and 12) with a percent difference of ~1%. Such a small percent difference indicates that the strain rate effects for conventional forming are relatively small.

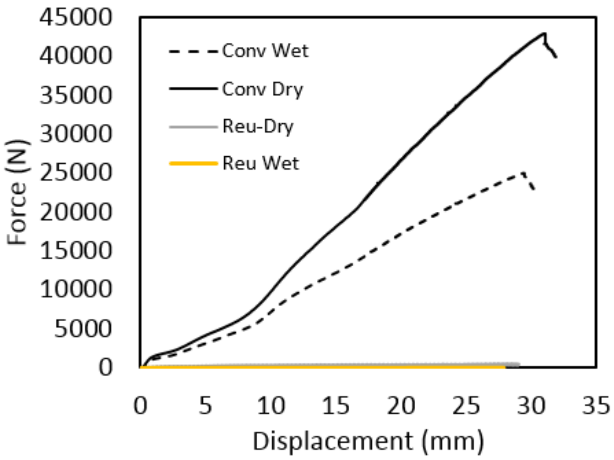

Figure 11. Comparison between the friction effects of conventional and Reuleaux tube forming

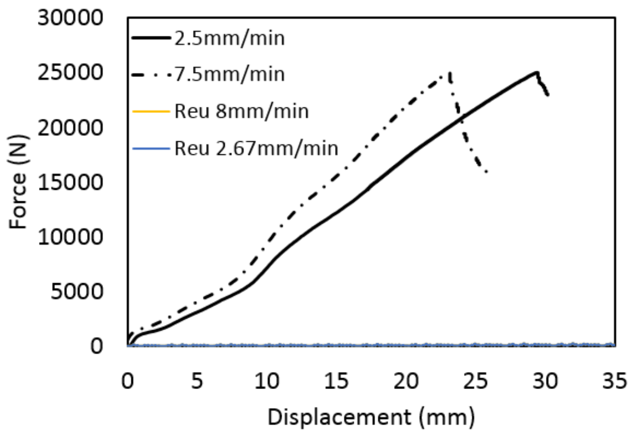

Figure 12. Comparision between the strain rate effects of conventional and Reuleaux tube forming

The maximum Z-direction force experience by Reuleaux tube forming at a strain rate of 5.33 mm/min, and 2.67mm/min, and 8mm/min were 498.6, 498.6, and 481.4 N. The percent difference between the max force experienced between the 5.33mm/min to the 2.67 mm/min and 8 mm/min are 9.5% and 3.33%. The strain rate effect on Reuleaux tube forming also play a small role. When compared the friction effect on Reuleaux forming it was observed that only 20% more force is required as compared to lubricated case, which is much lower than what it was experienced in conventional frictional effect (i.e., 72%). Figure 11 also indicated the drastic difference in force required to deform the tube between Reuleaux tube forming and conventional tube forming.

3.5 Wall Thickness of the 1018 steel test samples.

Figure 13 shows the wall thicknesses distribution for each experiment. For the conventional tube forming at 2.5, 5, 8 mm/min, localized thinning can be observed near the point of fracture (Figure 13a).

Comparing the Reuleaux triangle forming at 5.33mm/min and 2.67mm/min, it shows that the tubes experienced a more evenly distributed thickness without localization. However, at 8mm/min localized thinning occurred near the point of fracture (Figure 13b), but the gradient is not as dramatic when compared to the conventional tube forming.

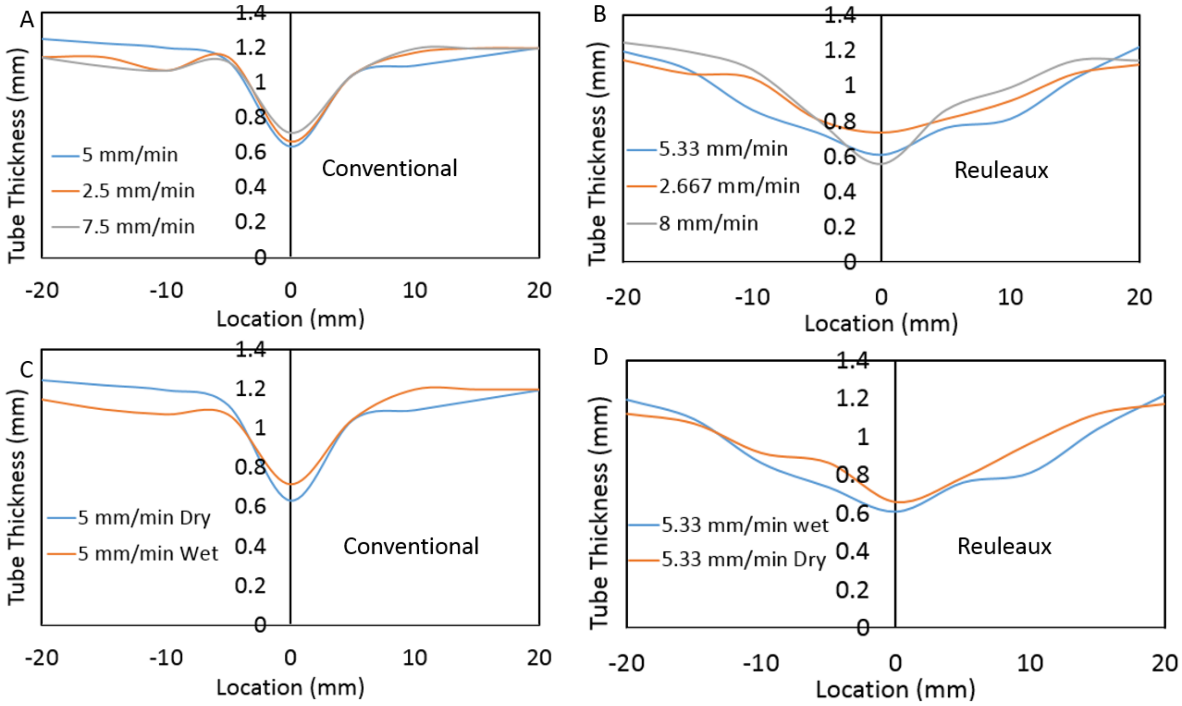

Figure 13. Graphs of the tube wall thickness at different conventional, Reulueax, and lubrication experiments.

The conventional tube forming at 5mm/min without lubrication also experiences the localized thinning but failure occurred earlier than the lubricated sample. However Reuleaux experiment with and without lubrication provides similar results and thus the results are insignificant for friction effect.

4. Conclusions

The paper focuses on the forming of square tube from circular section through flaring process. For this, a novel process to form the square shape was introduced in which the force required is much lesser that the conventional forming. For this various experiments were conducted and results were compared with conventional forming. In addition the strain rate and friction effect were are analyzed. It was observed that the newly introduced method i.e., Reuleaux forming only needs ~2% of force of what it was needed in conventional forming to form the same square tube. When compared the friction effect, the Reuleaux forming had no influence of friction and results were very similar. However for conventional forming without lubrication needed 72% more force to form the same tube section. This signifies that the effects of friction are much larger during conventional tube forming. The strain rate had insignificant effect on both conventional and Reuleaux forming. The thickness distribution was more uniform in Reuleaux forming as compared to the conventional forming.

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