Determination of Force During Wire Drawing of Copper

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Abstract

Copper wire has industrial application in building construction, power generation and transmission, electronic product manufacturing, and the production of industrial machinery and transportation vehicle. It is important to understand the effect of force during wire drawing of copper as this has direct impact on the die life span, the rate of production and the cost of production. This works involves theoretical investigation of force during wire drawing of copper. Copper drawing friction coefficient is 0.1071, reduction area is 0.19, die angle α is 5º, symmetry is denoted by n is 1 and Axisymmetry is denoted by n is 2.

From the results of the simulations, it was seen that for both symmetric and axisymmetric plane deformation, the coefficient of friction, die angle, reduction area has significant effects on the drawing force during the drawing process of copper. Three non-linear cases are considered, and from the results from the graphs in each of the cases it is noticed that a greater amount of force is required to draw the rod between the length of 0 to 0.5 and thereafter the effect of force is minimal and, in some cases, constant.

Each have a different behavior on force with the polynomial function being the highest and the natural logarithm being the lowest.

In this work, drawing force is determined through analytical and numerical method. Slab method is used to obtain the equations that dictate the drawing phenomenon, numerical solution is gotten using Runge Kutta and simulated using MATLAB.

Keywords

Wire drawing, Slab method, Drawing force, Copper

1. Introduction

Drawing is a metalworking process used to reduce the cross section of a wire by pulling the wire through a single or series of drawing dies(s). The reduction in diameter of a solid bar or rod by successive drawing is known as bar, rod, or wire drawing, depending on the diameter of the final product It is one of the oldest metal forming operations and it allows excellent surface finishes and closely controlled dimensions to be obtained in long products that have constant cross sections (Kahtan and Al-Naib 2014). Deformation of the rod is accomplished by a combination of tensile and compressive stresses that are created by the pulling force at the exit from the die.

Wire is one of the most important products required by man. Endless lengths of wire are used in the form of conductors in communication and power transmission. Enormous quantities of wire are used for fencing, cables for bridges and hoists. The products require correct dimension, surface finish and mechanical properties. Sizes vary from fraction of an inch to thousands of an inch. Wires are produced by the process of wire drawing. Drawing is different from extrusion because the wire is pulled rather than pushed through the die.

It is usually done at room temperature thus classified as a cold working process. Deformation in wire drawing is brought about by the process parameters, in wire drawing it is important to understand and define the relationship that exist between the process conditions and the resulting thermo-mechanical response of the wire.

Advantages of drawing are close dimensional control, good surface finish, improved mechanical properties such as strength and hardness and adaptability to economical batch or mass production. Understanding the relationship that exists between the process parameters which are the die angle, cross-sectional area reduction, friction coefficient and speed and the resulting thermos-mechanical response is important.

Improvement in the product quality can be obtained by optimizing the process parameter and this does not only improve the product quality but also reduce manufacturing cost. This paper presents an analytical study of how process parameters influence drawing force in wire drawing of copper.

The drawing force determination is important in that the drawn wire must have a sufficient resistance and cross-section to withstand the drawing effort without breaking, this helps to save the cost of carrying out expensive experimental procedure to determine this and other important design parameters to get a quality product. This particular project helps to study the effect of process parameters on the drawing force using a non-linear relationship.

1.1 Objectives

The aim of this research is to model the effect of drawing parameters that is die angle and area reduction on drawing force during wire drawing

The goal will be accomplished through the following objectives:

(i) Develop drawing model for the determination of force during wire drawing of copper

(ii) To numerically solve and simulate the developed drawing model for the determination of force during wire drawing of copper.

2. Literature Review

Drawing is a metalworking process of bars, rods and wires particularly used in the electric and automotive sectors. The process consists of reducing the cross-section by forcing the wire through series of dies (Vega et al. 2009).

This process is very similar to metal extrusion, the difference being in the application of force. In extrusion the work is pushed through the die opening, where in drawing it is pulled through. In the drawing process, a pulling force and a pressure force, from the die, combine to cause the wire to extend and reduce in cross-sectional area, while passing through the die, as a result of this combined effect, the pulling force or drawing force can be less than the force that would cause the wire to stretch, neck, and break from the die.

In the wire industry, to increase the productivity and reduce the manufacturing cost, the most effective way is to increase the drawing speed, which results in an increase of strain rate (He 2002). By definition, the friction is proportional to the normal tension at the wire/die interface. This friction produces heat because of the relative movement between the material and the die (Santana 2020).

The wiredrawing is a plastic metal forming process, generally performed at cold working conditions, in which a suitably clean and lubricant coated wire is pulled through a die, which is a rigid tool with wear resistant surface (Ikumapayi 2015).

In wire drawing of copper, the maximum equivalent strain increases due to the increase in friction forces that makes the deformation more inhomogeneous near to the die–wire interface (Rogas 2019). The main variables involved in this type of processes are: die semi angle, α, cross-sectional area reduction, r and friction coefficient, μ or m, for representing the friction along the die-workpiece interfaces, depending on if Coulomb friction or partial one is considered. Structural changes entrained by cold plastic deformation alter physical and mechanical properties of metals (Zidani 2012).

Drawing process is one of the most used metal forming process within the industrial field and, particularly, in automotive and electric sectors (Murty and Reddy 2016). It should be noted that the drawing capability process depends on three main parameters:

(i) The wire material properties.

(ii) The die geometries (such as die angle and die length) and

(iii) The processing conditions such as drawing speed and friction at the interface between the die and the wire (Vega et al. 2009).

Die wear is the predominant factor affecting tool life in the drawing process by thermal load and wire die contact during the deformation process (Haddi 2012). External friction between the wire and the drawing die is among the factors which determines the conditions of the top wire layer (Masse 2013). The prediction of die life is very important to achieve good quality of finished products.

The influence of the reduction zone as well as the bearing zone is known to significantly affect the drawing force, spatial profile of the radial stress, residual stress behavior, and properties of the resultant wire (Stolyarov 2019).

The deformation force mostly depends on a degree of deformation, mechanical properties of the work piece before and after drawing, a working angle of the channel of a die, as well as, a friction coefficient or a thickness of the layer of lubrication in the deformation zone (Platov 2017).

Among the existing analytical models to estimate the force necessary to produce the deformation, the analytical method called local stress analysis or slab method, based on the analysis of the state of equilibrium in the wire-die system just when the process reaches its stationarity, is the best known and has been used in many of the works consulted (Rodríguez-Alabanda et al. 2019).

3. Methods

Modeling the forces in wire drawing process

Consider an axisymmetric die and wire as shown in Figure 1, limited tension is applied to the working material and the maximum tension per unit area allowed on the material section during the drawing is equal to the yield stress as shown in Figure 1.

Where,

α – is the die angle

A_1 – Cross section area at the exit

A_0 – Cross section area at the entrance

μ – Coefficient of Friction

δ_x – Yield Stress

r – Reduction

δ_T – Forward Tension

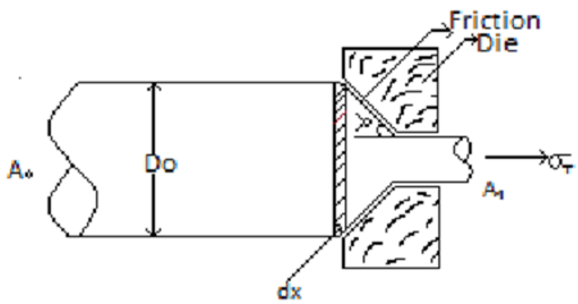

Figure 1. Axisymmetric die and wire.

The following assumptions were made in obtaining the drawing process model.

1. The die is considered a rigid body and the drawing material is considered a rigid plastic material.
2. The plastic deformation is plain strain.
3. The average stresses are uniformly distributed within the elements.
4. There is friction at the die material interface and the dynamic friction coefficient is constant (i.e., the friction obeys coulomb's law).
5. The material flows into and out of the system horizontally i.e., one-dimensional flow system prevails.
6. The die angle is small

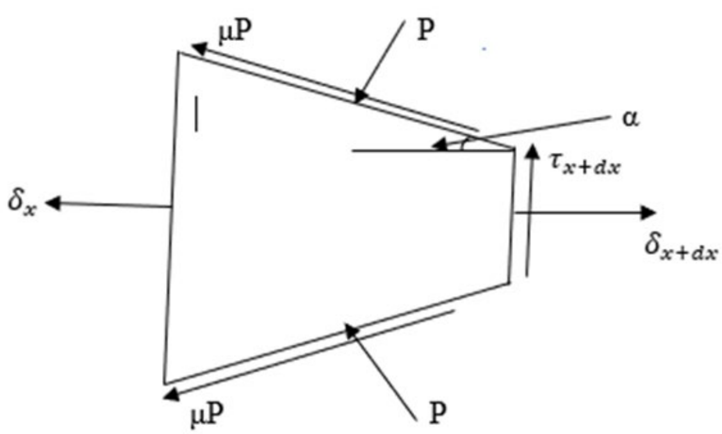

Figure 2. Material Element

Balancing the forces, the equilibrium equation in the x direction is

$$\sum F_x = 0 = \left(\delta_x + \frac{d\delta_x}{dx}\right)\frac{\pi R_{(x)}^2}{4} - \frac{\delta_x \pi R_{(0)}^2}{4} - 2\left(P\pi R_{(x)}\frac{dR}{2}\right) - 2\left(\frac{\mu P\pi R dR}{2tan\alpha}\right) = 0 \qquad \text{--- (1)}$$

Expanding the equation and collecting the like terms and multiplying through by $4tan\alpha,$ we have

$$\left[\boldsymbol{\delta_x R_{(x)}^2 + \frac{d\delta_x}{dx} R_{(x)}^2 - \delta_x R_{(0)}^2}\right] \boldsymbol{tan\alpha - PR_{(x)} tan\alpha dR - 4\mu PR_{(x)} dR = 0} \quad \text{--- (2)}$$

Dividing through by $\boldsymbol{R_{(x)}^2}$ gives

$$\left[\boldsymbol{\delta_x + \frac{d\delta_x}{dx} - \delta_x \left(\frac{R_0}{R_{(x)}}\right)^2}\right] \boldsymbol{tan\alpha - \frac{4P}{R_{(x)}} [\mu + tan\alpha] dR = 0} \quad \text{--- (3)}$$

$$\boldsymbol{R_0 = R_{(x)} + xtan\alpha}$$

$$\boldsymbol{R_{(x)} = R_0 - xtan\alpha}$$

$$\boldsymbol{1 = \frac{R_0}{R_x} - \frac{xtan\alpha}{R_{(x)}}}$$

$$\boldsymbol{\left(\frac{R_0}{R_{(x)}}\right)^2 = \left(1 - \frac{xtan\alpha}{R_{(x)}}\right)^2}$$

$$\boldsymbol{dR = tan\alpha \, dx}$$

$$\boldsymbol{tan\alpha = \frac{dR}{dx}}$$

So, we have

$$\boldsymbol{\left(\frac{R_0}{R_{(x)}}\right)^2 = \left(1 - \frac{xdR}{R_{(x)}dx}\right)^2} \quad \text{--- (4)}$$

Substituting equation (4) into equation (3), we have

$$\left[\boldsymbol{\delta_x + \frac{d\delta_x}{dx} - \delta_x \left(1 - \frac{xdR}{R_{(x)}dx}\right)^2}\right] \boldsymbol{tan\alpha - \frac{4P}{R_{(x)}} [\mu + tan\alpha] dR = 0}$$

Recall $\boldsymbol{tan\alpha = \frac{dR}{dx}}$

$$\boldsymbol{\frac{d\delta_x}{dx}\frac{dR}{dx} + \frac{2x\delta_x}{R(x)} \left(\frac{dR}{dx}\right)^2 - \frac{x}{R_{(x)}^2} \left(\frac{dR}{dx}\right)^3 - \frac{4P}{R_{(x)}} [\mu + tan\alpha] dR = 0} \quad \text{--- (5)}$$

The above equation is the developed equation for the forces however, $\left(\frac{dR}{dx}\right)^{3} \simeq \mathbf{0}$, so we have

$$\left[\frac{d\delta_x}{dx} + \frac{2x}{R(x)}\,\delta_x \frac{dR_x}{dx}\right] tan\alpha - \frac{4P}{R_{(x)}}[\mu + tan\alpha]dR = 0$$

Since $tan\alpha = \frac{dR}{dx}$

$$dx = \frac{dR}{tan\alpha}$$

$$\frac{d\delta_x}{dx} + \frac{n}{R(x)}\left[\delta_x \frac{dR_x}{dx} - P(\mu + tan\alpha)\right] \quad \text{---(6)}$$

Where the constant n allows generalization of the equations for balancing forces.
n = 1 for the problem of symmetric plane deformation
n = 2 for the problem of axisymmetric plane deformation
using the dimensionless parameters X of position x

$$X = \frac{nxtan\alpha}{Ro\left(\frac{A0-A1}{A0}\right)}$$

$$x = \frac{XR_0\left(\frac{A0 - A1}{A0}\right)}{ntan\alpha}$$

$$x = \frac{XR_0 r}{ntan\alpha}$$

Where,

$$r = \frac{A0 - A1}{A0}$$

For the conical dies, the contact zone between the die and the material has its slope defined by

$$\frac{dR}{dx} = -tan\alpha$$

i.e., from

$$R_{(x)} = R_0 - xtan\alpha$$

$$R_{(x)} = \left[R_0 - \left(\frac{XR_0 r}{n\,tan\propto}\right)\right] tan\alpha$$

$$R_{(x)} = R_0\left(1 - \frac{x}{R_0}\,tan\alpha\right)$$

Therefore, equation (6) becomes

$$\frac{d\delta_x}{dx} - \frac{r}{\left(1-\frac{x}{R_0}\frac{r}{n}\right)tan\alpha}\left[\delta_x\, tan\alpha + P(\mu + \tan\alpha)\right] = 0 \quad \text{--- (7)}$$

3.1 linear pressure

When the die pressure is linear P = A - Bδ_x

Putting the value of P into equation 7 we have,

$$\frac{d\delta_x}{dx} - \frac{r}{\left(1-\left(\frac{r}{n}\right)X\right)tan\alpha}\left[\delta_x\, tan\alpha - (A - B\delta_x)(\mu + \tan\alpha)\right] = 0 \quad \text{--- (8)}$$

Given the Initial Boundary condition

X = 0, x = 0

The above expression can be written as

$$\delta_x = \frac{A(tan\alpha+\mu)}{tan\alpha+B(tan\alpha+\mu)}\left[1 - \left(1 - \left(\frac{r}{n}\right)X\right)^{\frac{1}{ntan\alpha}[tan\alpha + B(tan\alpha + \mu)}\right. \quad \text{---(9)}$$

In real life situation the relationship between the pressure and stress is a nonlinear function so considering exponential and polynomial functions we have the following cases.

3.2 Exponential Nonlinear Function

When the die pressure is nonlinear P = Ae^{δ_x}

$$\frac{d\delta_x}{dx} - \frac{r}{\left(1-\left(\frac{r}{n}\right)X\right)tan\alpha}\left[\delta_x\, tan\alpha + P(\mu + \tan\alpha)\right] = 0 \quad \text{--- (10)}$$

$$\frac{d\delta_x}{dx} - \frac{r}{\left(1-\left(\frac{r}{n}\right)X\right)tan\alpha}\left[\delta_x\, tan\alpha + (\mathrm{A}e^{\delta_x})(\mu + \tan\alpha)\right] = 0 \quad \text{--- (11)}$$

3.3 Polynomial Nonlinear Function

When the die pressure is linear P = A + B $\delta_x + C\,\delta_x{}^2$

$$\frac{d\delta_x}{dx} - \frac{r}{\left(1-\left(\frac{r}{n}\right)X\right)tan\alpha}\left[\delta_x\, tan\alpha + P(\mu + \tan\alpha)\right] = 0 \quad \text{--- (12)}$$

Putting in the values P,

$$\frac{d\delta_x}{dx} - \frac{r}{\left(1-\left(\frac{r}{n}\right)X\right)tan\alpha}\left[\delta_x\, tan\alpha\, + (\mathrm{A} + \mathrm{B}\,\delta_x + C\,\delta_x{}^2)(\mu + \tan\alpha)\right] = 0 \quad \text{--- (13)}$$

3.4 Natural Logarithm Nonlinear Function

When the die pressure is linear P = A$ln\delta_x$

$$\frac{d\delta_x}{dx} - \frac{r}{\left(1-\left(\frac{r}{n}\right)X\right)tan\alpha}\left[\delta_x\, tan\alpha\, + P(\mu + \tan\alpha)\right] = 0 \quad \text{--- (14)}$$

Putting in the values P,

$$\frac{d\delta_x}{dx} - \frac{r}{\left(1-\left(\frac{r}{n}\right)X\right)tan\alpha}\left[\delta_x\, tan\alpha\, + (\mathrm{A}ln\delta_x)(\mu + \tan\alpha)\right] = 0 \quad \text{--- (15)}$$

Equations 11, 13 and 15 cannot be solved analytically so the numerical method Rung-Kutta was used. After solving the above equation numerically using Runge-Kutta, simulations are carried out using MATLAB. The experimental constants are given by the work of (Kabayama et al. 2009) and the result obtained by simulation is compared with experimental result of (Hassan and Hashim 2015). There is high degree of similarity between the result obtained experimentally and the simulation of the model.

5. Results and Discussion

5.1 Numerical Results

In the present study the effect of process parameters, which are the die angle, friction coefficient and reduction area on the drawing force is being investigated.

The slab method is used in the analytical method and then MATLAB is used for the numerical simulation. Three non-linear cases are being considered and the results being gotten from the cases are presented here. The Non-Linear case was carried out using Numerical Method Runge Kutta. Symmetric and Asymmetric planes was considered for the Non-Linear cases.

The color red, blue and black were used to represent the effects of different die angles and reduction area on the drawing force. Also, in each of the cases we considered the effect of each of these process parameters with regards to Symmetry die and Axisymmetric die. The results observed in each of these cases is discussed below.

We considered three non-linear cases of when P = Ae^{δ_x}, P = A ln δ_x and P = A + B $\delta_x + C\,\delta_x{}^2$. Then the observation of these three cases were also discussed.

5.2 Graphical Results

The Figure 3 shows the effect of process parameter on the drawing force, the die angle of 5º, reductions r of 0.1,0.14, 0.18 and a friction coefficient equal to 0.1071 was used, the figure reveals three distinct curves which correspond to the three solutions obtained.

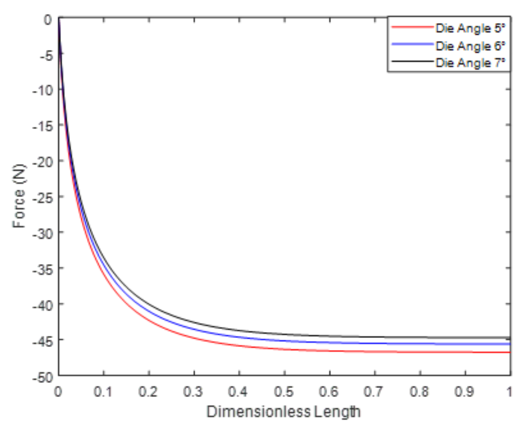

Figure 3a. Plot of force against dimensionless length considering Non-Linear exponential function when r is 0.10

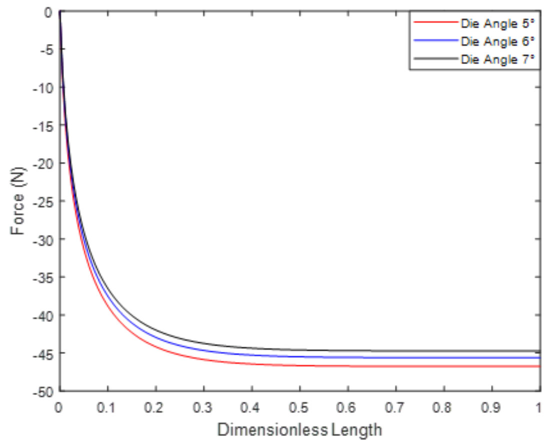

Figure 3b. Plot of force against dimensionless length considering Non-Linear exponential function when r is 0.14

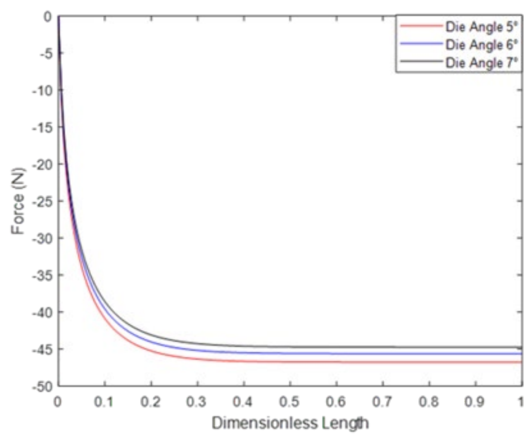

Figure 3c. Plot of force against dimensionless length considering Non-Linear exponential function when r is 0.18

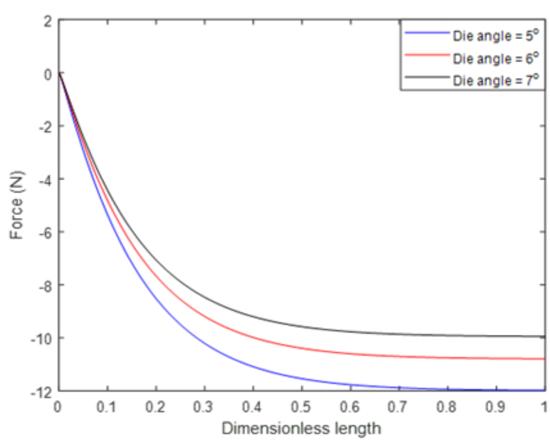

Figure 3d. Plot of force against dimensionless length considering Natural Logarithm Function when r is 0.10

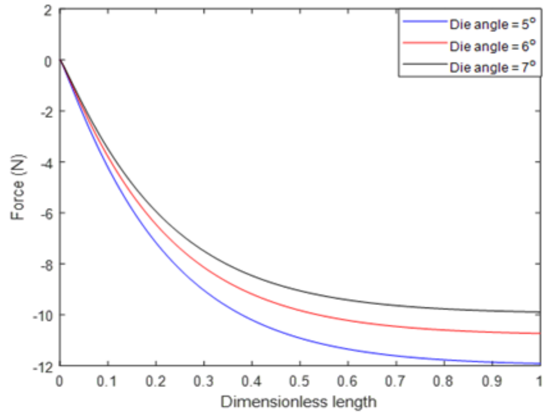

Figure 3e. Plot of force against dimensionless length considering Natural Logarithm Function when r is 0.14

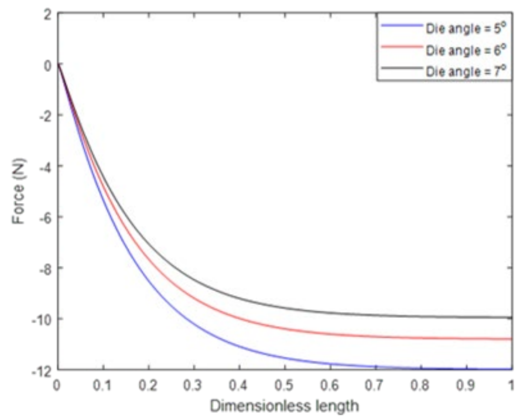

Figure 3f. Plot of force against dimensionless length considering Natural Logarithm Function when r is 0.18

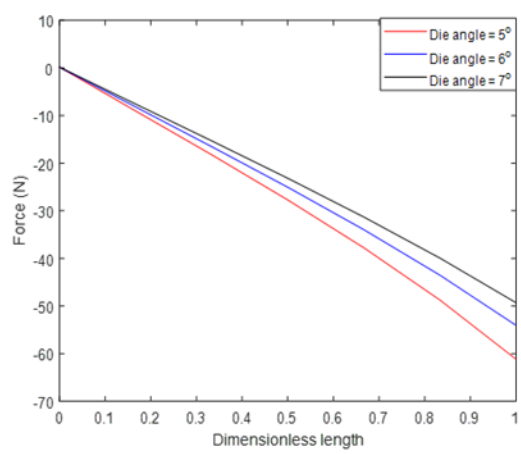

Figure 3g. Plot of force against dimensionless length considering Polynomial Function when r is 0.10

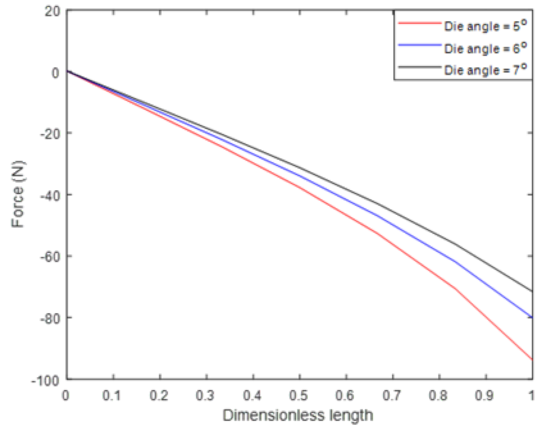

Figure 3h. Plot of force against dimensionless length considering Polynomial Function when r is 0.14

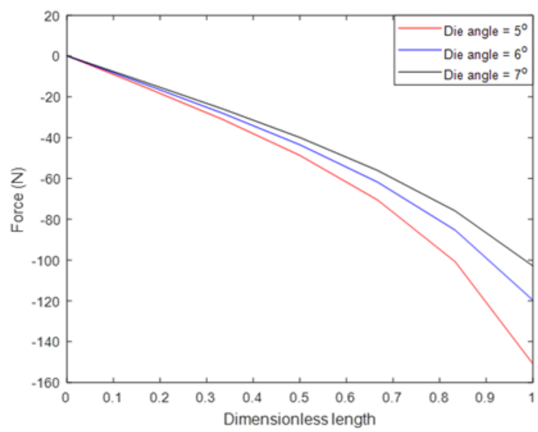

Figure 3i. Plot of force against dimensionless length considering Polynomial Function when r is 0.18

Figure 3. Plot of force against dimensionless length considering Non-Linear exponential function a, b, c, natural logarithm functions, d, e, f and polynomial function g, h, i.

Figure 3 (a), (b), (c) shows the result of the non-linear exponential function with Axisymmetry n is 2 it was observed that a high amount of force is required to draw the die from length 0 to 0.2 there after the amount of force required is slight. Then the greater the value of the reduction in area the greater the amount of force required to draw the die and at a reduction area of 18% the highest value of force was 0.3 length. Three reduction areas were considered with figure (a) being 0.10, figure (b) 0.14 and figure (c) 0.18. It is noticed that at 0.10 reduction the amount of force is not that much and when its value was increased to 0.14 its value of force also increased, it got higher at 0.18.
Figure 3 (d), (e), (f) shows the result of the non-linear natural logarithm function, symmetric n is 1 is used and it is seen that unlike in the exponential case a much higher value of force is require to get the same value of length. Also unlike in the exponential case a high amount of force is required to draw the die from length 0 to 0.4 there after the amount of force required is slight.
Figure 3 (g), (h), (i) shows the result of the non-linear polynomial function, the display of the curve is completely different unlike when non-linear cases of natural logarithm and exponential was considered. From the graph it is noticed that similar to the natural logarithm and exponential cases the value of the force is much greater from 0 to 0.5 then there after it decreases.

5.3 Proposed Improvements

I will recommend that more studies on non-linear relationship should be studied in terms of other process parameters and other numerical and analytical method should be looked into especially since the real-life effect of process parameter on force is non-linear in nature.

5.4 Validation

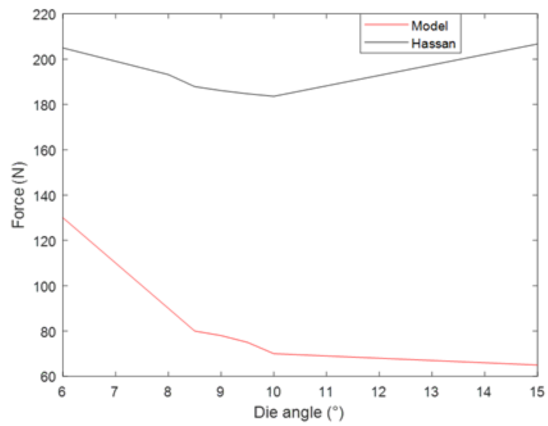

Figure 4. Figure 4. Comparison of the Experimental result of (Hassan and Hassim 2015) and the simulation of slab method

Figure 4. shows the comparison of the Experimental result of (Hassan and Hassim 2015) and the simulation of slab method of the present work. From the graph it can be seen that in the work of (Hassan and Hassim 2015) as the die angle increases the drawing force decreases until we get to a die angle of 10° it is noticed that instead of the drawing force to decrease it kept increasing this is because the redundant stress increased with increasing die angle.
In the present work from the result of our simulation it is found that the behavior of the drawing force and die angle was as expected which is that an increase in the die angle results to a decrease in the drawing force.

6. Conclusion

From the results of the simulations, it can be seen clearly that for both symmetric and axisymmetric plane deformation, the coefficient of friction, die angle, reduction area has significant effects on the drawing force during the drawing process of copper. Three non-linear cases are considered, and from the results from the graphs in each of the cases it is noticed that a greater amount of force is required to draw the rod between the length of 0 to 0.5 and thereafter the effect of force is minimal and, in some cases, constant. When considering the effect of die angle at different reductions in area it is observed that for the exponential function and the natural logarithm function the value of force is the same at length 0.5 and above but varies in the polynomial function.
Each have a different behavior on force with the polynomial function being the highest and the natural logarithm being the lowest. Although the relationship between the drawing force and the process parameter being studied is non-linear unlike past literature in which the relationship is mostly linear it is seen that the non-linear relation exhibits a similar pattern to the linear relation.

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