Friction in Metal-Forming Processes: Design of a Slidometer to Measure Friction in Sheet-Metal Forming

Submitted by

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Abstract

Sheet metal forming is a reliable, cost-effective method to forming metal into different parts. However, the outcome of this process is significantly influenced by many different factors including material properties, lubrication, and forming processes. Friction plays a crucial role in this process by influencing the overall part quality, tool life, and cost of production. An analysis of the effects of friction in sheet metal forming was performed, along with studies of current methods of measuring friction in sheet metal forming. Two conceptual slidometers were designed to measure friction using different methods, and both designs were analyzed. Continual studies will be performed to develop a better understanding of friction in metal forming processes.

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Introduction

Metal forming processes are common in every industry, yet the underlying complexity of these processes is significantly greater than it may seem. As metals are shaped through different processes, what is happening between the two surfaces affects the overall outcome of the part. Because of this, a focus has been placed on understanding many aspects of metal forming, specifically analyzing the effects of friction on different metal forming processes. Numerous studies have been performed to improve knowledge of the role that friction plays in metal forming processes such as sheet metal forming, yet there still lacks a fully inclusive method of measuring friction.

Sheet metal forming is a common method of metal forming, especially in automotive applications. Because sheet metal forming can be utilized to produce large amounts of parts in short production times, it is a reliable, inexpensive way to shape metal. In this process, a piece of sheet metal is placed between a punch and die surfaces. A force is applied to the punch to mold the sheet metal to the shape of the die. In doing so, the sheet metal is formed to the desired shape.

The effects of friction during this process have substantial impacts on many factors including part quality, tool life, and overall production costs. Tribology, or the measurement of friction, is aimed at understanding the interactions between different factors related to the surface of sheet metal [1]. Harmful effects of friction include increasing forces required for forming, increasing tool wear, and increasing produce surface defects [2]. Understanding methods to mitigate these negative effects is important, yet friction is a complex phenomenon that requires involved testing and analysis. The value of the coefficient of friction changes throughout the sheet metal forming process based on factors such as time, location on the sheet metal surface, geometry, contact between the tool and sheet metal, surface condition, lubrication, deformation rate, and local temperature [2]. The interaction between all these variables makes it difficult to analyze the relationship between a single variable and its effect on friction. Therefore, efforts have continued to focus on developing slidometers, or tools to measure friction, to be used in the sheet metal forming process to better understand how friction evolves throughout the process and effects the outcome of the product. This is crucial to the development of more accurate models to simulate sheet metal forming which are used in the design and development stages of production.

Conceptual Design

In the most basic terms, the coefficient of friction can be defined as a material property describing the amount of friction between two surfaces according to the following equation:

$$\mu = \frac{F_f}{N} \tag{1}$$

Where: μ is the coefficient of friction, F_f is the friction force, and N is the normal force.

From Equation 1 it can be concluded that the coefficient of friction during the sheet metal forming process can be calculated as the ratio of a measured friction force to a known normal force. However, the actual measurement of these two forces is difficult and changes based on many different material, lubricant, and process factors. Additionally, the phenomenon of friction is more complex than this equation suggests as conditions across the sheet metal material are continually changing, resulting in non-uniform values for the coefficient of friction throughout the process.

On a small scale, friction is a result of the ploughing and adhesion effects between asperities of two contacting surfaces [3]. No matter how smooth a surface appears, there are bumps and rough areas on the surface. Contact between these areas on two surfaces are where the effects of friction are evident. The ploughing and adhesion effects are dependent on the real area of contact between two surfaces, which depends on forces such as normal loading, flattening, and stretching [3]. As either surface is subjected to these forces, the area of real contact changes, thereby decreasing or increasing the friction between surfaces. The greater the real contact area between two surfaces, the greater the friction. Therefore, reducing the real contact area between to surfaces in the sheet metal forming process helps to mitigate the negative effects of friction.

Friction Parameters

Many parameters effect the overall coefficient of friction present in the sheet metal forming process. The tribological properties of both the sheet metal and die that influence the effects of friction on the forming of the part include material properties, lubrication properties, surface roughness, punch and die radii, and process conditions [4]. The effects of each are examined below.

Material Properties: The properties of both the sheet metal and tooling are crucial to the sheet metal forming process. Both the forming process and the intended application for the part must be considered when determining the metal to use. Sheet metals must be able to withstand the forces applied in the forming process without fracturing. Material properties such as stretch distribution, strain hardening exponent, plastic strain ratio, and surface topography must be considered when selecting a sheet metal material [5]. Furthermore, the effects of temperature on the material properties must be considered to ensure that the metal is compatible with the forming conditions.

Lubrication: Lubrication plays a crucial role in metal forming processes and can be used to mitigate the negative effects of friction. However, the effectiveness of lubrication depends on several factors: amount of lubricant, forming speed, load, and viscosity. Based on the Stribeck Curve seen in Figure 1, the ideal lubrication film thickness minimizes the coefficient of friction. In the boundary lubrication region, common in metal forming processes, there is a thin layer of lubrication between the two surfaces but contact between asperities is prevalent [7]. This results in higher coefficients of friction. In the mixed lubrication region, the coefficient of friction decreases with an increase in viscosity and speed, a decrease in the normal load applied, and an increase in the film thickness [6]. In this region, the lubrication fills the micro-valleys of the surfaces, resulting in a layer of lubrication between the micro-peaks and micro-valleys [7]. This decreases the real contact area and therefore also decreases the friction between the two surfaces. In the hydrodynamic lubrication region, used in few sheet metal forming processes, there is a thick layer of lubrication between the two surfaces. This causes the coefficient of friction to increase as this layer of fluid creates a lifting pressure [7]. Additional factors are considered when determining the best lubrication to use for a given sheet metal forming process, including method of application, additives, corrosion control, and removal methods [7].

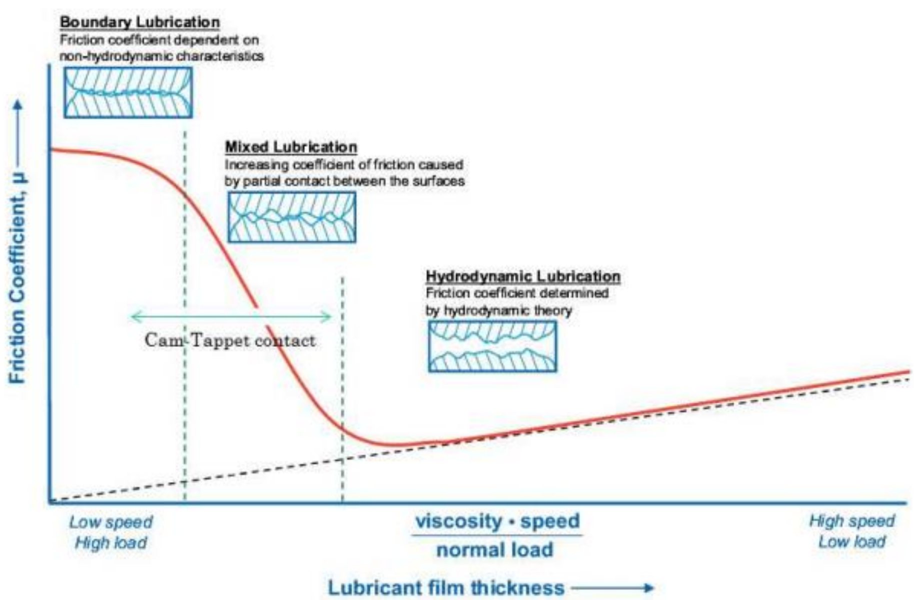


Figure 1. Stribeck Curve: Friction Coefficient vs Lubrication Film Thickness [6]

Surface Roughness: The surface roughness of both the tool and sheet metal significantly influence the friction that occurs during sheet metal forming. The amount of friction between surfaces depends on the real contact area between the surfaces such that an increase in the contact area increases the friction between surfaces. Decreasing the real contact area by increasing surface roughness would result in a lower coefficient of friction. However, direct contact between sheet metal and tooling, obtained through smooth surface contact, results in deformation of sheet metal as intended in the sheet metal forming process. This is because of the plastic deformation that takes place between two smooth surfaces whereas rough surfaces result in streaking and poor part quality [2]. In a study by Sigvant, the effects of surface roughness were studied in a simulation of sheet metal forming. It was concluded that an increase in surface roughness, both tool roughness and sheet metal roughness, resulted in an increase in the coefficient of friction present [8]. This can be seen in Figure 2.

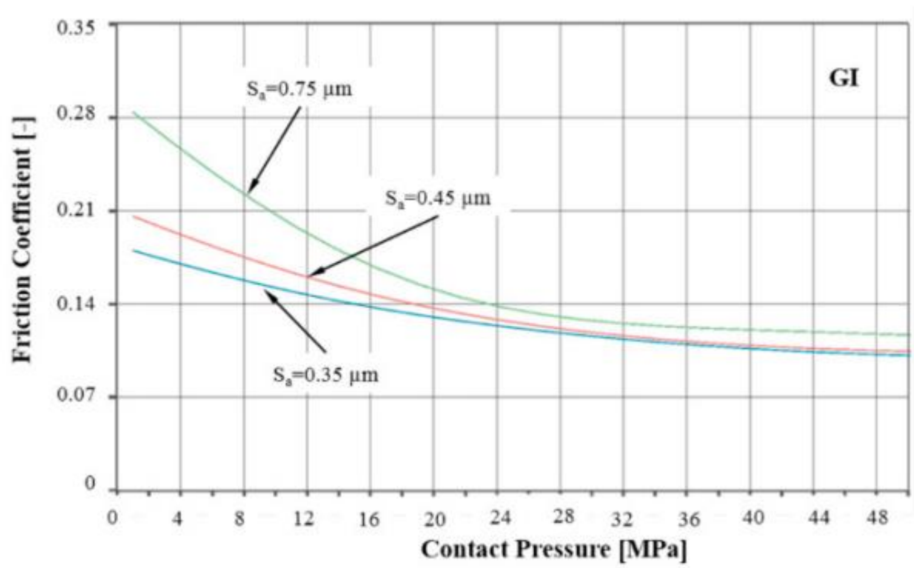


Figure 2. Friction Coefficients as a Function of Contact Pressure and Surface Roughness [8]

Punch and Die Radius: The punch and die radii influence the amount of force necessary to form the sheet metal. The smaller the radius of the die and punch, the greater the force necessary to shape sheet metal during stamping and the more likely it is that tearing will occur [9]. Furthermore, increasing the punch radius would decrease the pressure applied to the sheet metal as the contact area of the force is increased. This would result in an increase in the coefficient of friction, as seen in a study by Sigvant shown in Figure 2 [8]. Therefore, the punch and die radii should be maximized to prevent large forming forces, friction, and part blemishes.

<u>Process Conditions</u>: Forming process conditions such as temperature, forming speed, and applied pressure effect the friction present in the sheet metal forming process. At higher temperatures, the coefficient of friction tends to increase as adhesion at the contact surfaces increases [10]. This means that the negative effects of friction are more prevalent in hot forming processes than cold forming. Galling also increases at higher temperatures, meaning that elevated temperatures not only increase friction, but also reduce part quality [10]. However, the effect of temperature on lubrication must also be considered. According to experimental ball-on-disc tests performed by Wu et. Al., increasing the temperature in sheet metal stamping influences the performance of lubrication and can reduce the shear strength of the coating, thereby decreasing the coefficient of friction [10]. At higher drawing speeds, the coefficient of friction decreases, as proven in an experiment performed by Ju et. Al. seen in Figure 3 [11]. Increasing the contact pressure of the punch during sheet metal forming reduces the coefficient of friction, according to a study by Sigvant. The results of this study are seen in Figure 2 [8]. According to Leocata et. Al, the contact pressure has a greater impact on the coefficient of friction compared to the sliding speed [12].

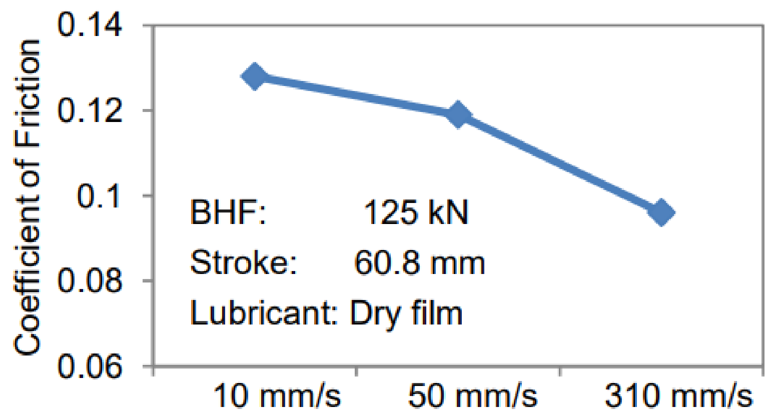


Figure 3. Friction Coefficient as a Function of Drawing Speed [11]

Friction Models

Friction can be modeled using several different equations, but the Coulomb friction model and the shear friction model are the most common.

Although the Coulomb Friction Model has several limitations to its accuracy, it is commonly used to describe the friction in sheet metal forming processes. In this model, the friction force is proportional to the normal pressure using a coefficient of friction [10]. Equation 2 is used to define friction according to this model [7].

$$\tau_f = \mu p \tag{2}$$

Where τ_f is the frictional shear stress, μ is the coefficient of friction, and p is the normal pressure. Coulomb's friction model is fairly accurate for low and medium range loads, making it useful in determining friction in sheet metal forming [13]. However, it does not incorporate factors such as contact behavior, punch speed, deformation, etc. [3]. Furthermore, this model is not accurate at high pressures where $\tau_f < \mu p$ and the linear relationship between τ_f and p given by Coulomb's model is not valid [7]. To overcome this limitation of Coulomb's friction model, the shear friction model was created.

The Shear Friction Model was proposed to account for friction at high pressures and can be defined by the following equation [7].

$$\tau_f = f\bar{\sigma} = m\frac{\bar{\sigma}}{\sqrt{3}} = mk \tag{3}$$

Where τ_f is the frictional shear stress, f is the friction factor, m is the shear factor, k is the shear strength, and $\bar{\sigma}$ is the flow stress of the deforming material.

At low pressures, the shear friction model is equivalent to the Coulomb friction model. However, at high pressures, the shear friction model gives a constant value for friction, as seen in Figure 4.

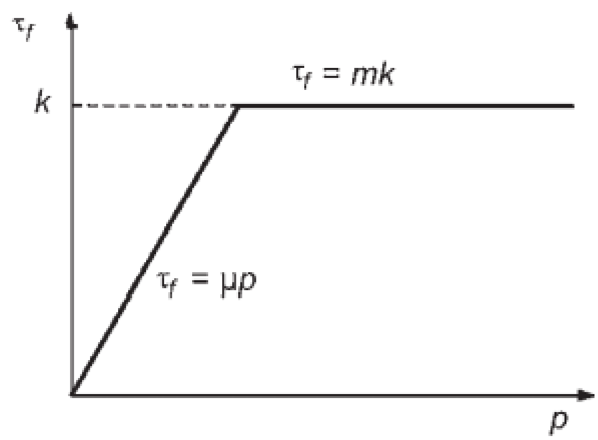


Figure 4. Shear Friction Model [7]

The shear friction model was modified by Wanheim and Bay to account for the real contact area between two surfaces according to the following equation [7].

$$\tau_f = f'\alpha k = m_r\frac{\bar{\sigma}}{\sqrt{3}} \tag{4}$$

Where τ_f is the frictional shear stress, f' is the modified friction factor, m_r is the modified shear factor, $\bar{\sigma}$ is the flow stress, and α is the real contact area ratio ($\frac{A_r}{A_a}$).

This model shows that the friction shear stress is directly proportional to the real contact area such that increasing the real contact area increases the friction between two surfaces.

Further modifications were made to this model by Bowden and Tabor to account for lubrication based on the following equation [7].

$$\tau_f = \alpha\tau_a + (1-\alpha)\tau_b \quad (5)$$

Where τ_f is the frictional shear stress, α is the real contact area ratio ($\frac{A_r}{A_a}$), τ_a is the average shear stress at contacting asperity peaks, and τ_b is the average shear stress at the lubricant pockets.

This illustrates that the frictional shear stress can be minimized by using lubricant to reduce the shear stress at the contacting asperity peaks and the lubricant pockets. However, the frictional shear stress is still dependent on the real contact area between the surfaces.

Although this model accounts for more variables than the Coulomb friction model, it is more difficult to apply in sheet metal forming simulations. Therefore, the Coulomb friction model is more commonly used to understand the effects of friction in the sheet metal forming process.

Experimental Test Methods

To understand friction more accurately in sheet metal forming, several different experimental test methods have been developed. These different testing methods impact the calculated coefficient of friction. Of these tests, the following three are common: Bending Under Tension Tests, Strip-Reduction Tests, and Drawbead Tests.

The Bending Under Tension Test was developed by Littlewood and Wallace and uses a cylindrical counter sample to draw a strip of metal around [10]. This method is illustrated in Figure 5 and uses the two force measurements to calculate the coefficient of friction using the following formula.

$$\mu = \frac{2}{\pi} \ln \left(\frac{F_1}{F_2}\right) \quad (6)$$

Where μ is the coefficient of friction and F_1, F_2 are the forces indicated in Figure 5.

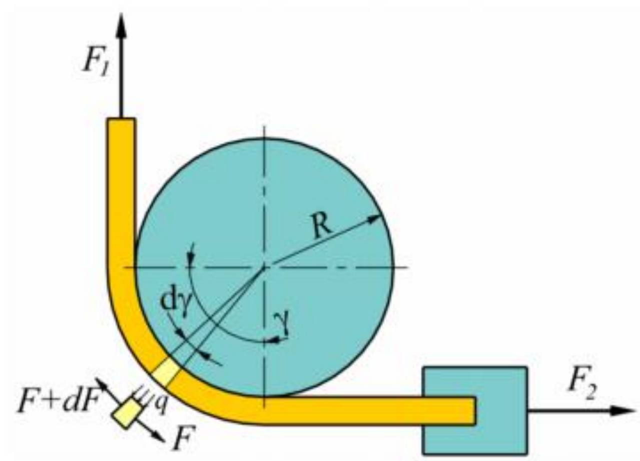


Figure 5. Bending Under Tension Test Method [10]

Many different versions of Bending Under Tension tests have been designed to understand how friction changes during the process of bending the sheet metal over the roller. This testing method allows for the determination of a coefficient of friction without measuring the strain [10]. The Bending Under Tension test uses a simple testing mechanism, making it easy to measure lubricant quality, but is limited in its ability to measure sheet metal forming at different bending angles [4]. Another limitation to this testing method is that it does not allow for the direct measurement of the force applied to the center of the specimen, resulting in errors in the calculated coefficient of friction if the sheet metal material is strain sensitive [10].

The Strip-Reduction Test was created to simulate the ironing process of sheet metal forming in which there are high pressures, low slipping speeds, and surface expansion [10]. In this test, a piece of sheet metal is forced through two stationary dies to decrease the thickness of the strip, as seen in Figure 6.

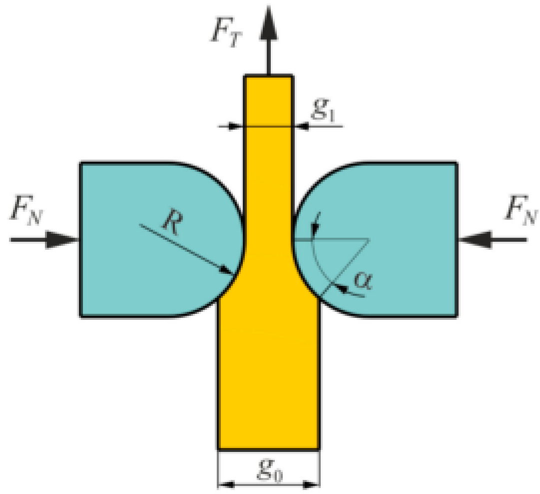


Figure 6. Strip-Reduction Test Method [10]

As the sheet metal is forced through the two dies, the coefficient of friction can be calculated according to the following equation.

$$\mu = \frac{F_T - 2F_N \tan\alpha}{2F_N + F_T \tan\alpha} \tag{7}$$

Where α is the angle indicated in Figure 6 and F_T, F_N are the forces labeled in Figure 6.

Strip reduction tests are beneficial in their ability to analyze the effect of different lubrications in the ironing forming process. However, this test is limited in its ability to simulate testing with long sliding lengths and cannot handle multiple strokes with idle time between strokes [14]. These factors limit the accuracy of the strip reduction test in simulating ironing conditions and properly analyzing the effects of friction in sheet metal forming.

The Drawbead Test is used to measure the friction present in sheet metal forming by separating the deformation force from the frictional force [10]. This is performed by pulling a piece of sheet metal over fixed and rotating rollers while measuring the pulling and clamping forces [10]. This method can be seen in Figure 7.

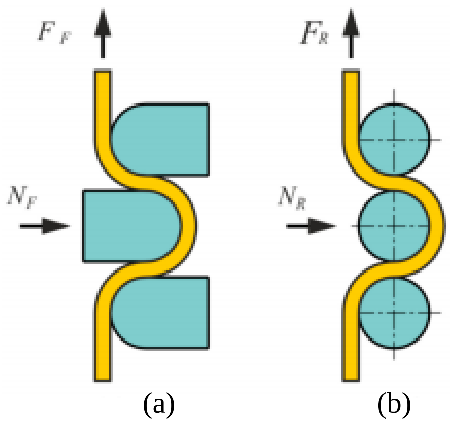


Figure 7. Drawbead Test Method with Fixed (a) and Rotating (b) Rollers [10].

Based on the drawing force measured in the drawbead tests using both the rotating and fixed rollers, the coefficient of friction can be calculated using this test according to the following equation [10].

$$. \mu = \frac{F_F - F_R}{\pi N_F} \quad (8)$$

Where F_F and F_R are the pulling forces using the fixed and rotating rollers, respectively and N_F is the normal force or clamping force.

As a result of this test, the sheet metal strip is bent from the applied force, as seen in Figure 8. As multiple passes are made of the sheet metal through the drawbead inserts, the surface roughness to decreases [12].

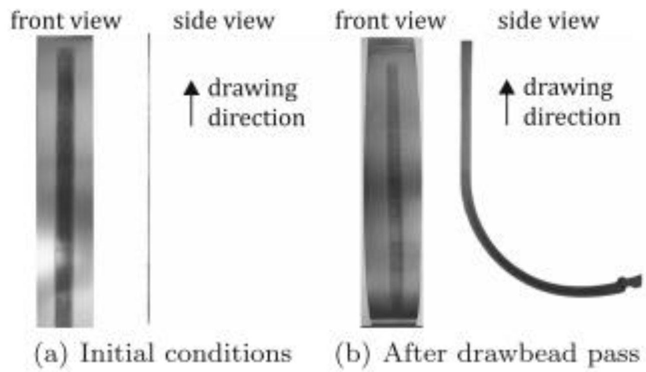


Figure 8. Sheet Metal Before and After a Drawbead Test [12].

One limitation of the drawbead simulation test is that it doesn't reflect the change in the coefficient of friction in different regions caused by different stress modes [4]. However, this test is useful in its ability to test different lubrication methods by varying the type and amount of lubrication used on the sheet metal. One of the conceptual slidometers developed in this paper was designed to be used in a drawbead test.

Although these tests are not entirely accurate in their simulation of the sheet metal forming process, they are able to simulate this process on a small scale. This gives a better understanding of the stresses and strains experienced during sheet metal forming, along with increased knowledge of the effects of different lubricants. This helps to identify methods to minimize friction and make sheet metal forming produce better parts in a more cost-effective way.

Slidometer Designs

Since friction significantly impacts the quality of the sheet metal part produced, along with the tool life and production costs, much research has been performed to develop an accurate way to measure friction. Many friction measuring devices, or slidometers have been designed with the goal of obtaining a more accurate value for the coefficient of friction. The following two slidometers were studied: a variable incidence tribometer and a portable inclinable articulated strut slip tester.

A variable incidence tribometer is used to measure the coefficient of friction between two surfaces based on the relationship between the forces and the angle between them. The schematic shown in Figure 9 illustrates the working principle of this design. By increasing the tile angle α until slippage occurs, the coefficient of static friction can be determined according to the following equation.

$$. \mu = \frac{F_T}{F_N} = \frac{mg \sin \alpha}{mg \cos \alpha} = \tan \alpha \tag{8}$$

Where F_N is the normal force, F_T is the friction force, and α is the incline angle.

The angle can continue to be adjusted until the slipping of the object occurs at a constant velocity [15]. Using several sensors, the moment and angle at which slippage occurs can be determined to calculate the coefficient of friction.

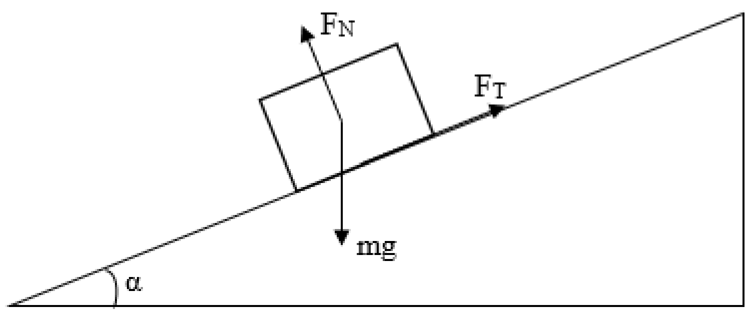


Figure 9. Variable Incidence Tribometer Principle.

The variable incidence tribometer illustrated in Figure 10 can provide an approximate value for the coefficient of friction. However, there is a limitation to this slidometer design in the fact that it cannot account for the velocity of the movement [15]. Furthermore, the slipping may need to be initiated manually, making it inaccurate and producing error in the experimental coefficient of friction determined using this method [15].

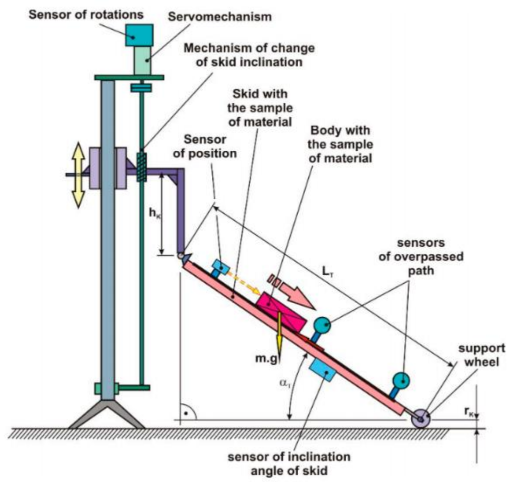


Figure 10. Design of a Variable Incidence Tribometer [15].

Another slidometer design is the portable inclinable articulated strut slip tester (PIAST), illustrated in Figure 11.

Figure 11. Design of a Portable Inclinable Articulated Strut Slip Tester [16].

This slidometer was initially designed to measure the friction between a shoe and the floor, but the operating principle is valuable to developing a conceptual slidometer to measure friction in the sheet metal forming process. The PIAST applies both a normal and parallel force to the floor at the same time [16]. By setting the PIAST to a given angle, a force is applied at the tip of the slidometer. This force is applied at an angle, so the normal and parallel components can be calculated [16]. If a selected angle does not result in slippage at the slidometer-floor interface, the angle must be adjusted until slippage occurs. This slidometer can be useful in experimentally measuring the effects of different lubrication methods, yet the angle must be adjusted for slippage to occur.

These slidometers all can be used to experimentally determine coefficients of friction, yet there still lacks an accurate way to determine the frictional effects in sheet metal forming. Through the design of two different slidometers, this paper serves to design a way to measure friction in sheet metal forming so that a more reliable coefficient of friction can be used in sheet metal forming simulations.

Experimental Design

Upon consideration of the nature of friction during the sheet metal forming process, two distinct slidometer designs were created to measure an experimental coefficient of friction. Both designs utilize the Coulomb Friction measurement method by calculating the coefficient of friction as the ratio of the friction force to the normal force. However, these slidometers were designed for two different methods of friction measurement.

Design 1

An initial slidometer design was created to measure the friction along the surface of a 3-dimensional die at various locations to understand how the coefficient of friction changes between locations. To do this, the slidometer utilized two spring driven pistons to apply a normal and radial force to a small piece of sheet metal against the die surface. Using load cells to measure both applied forces, the coefficient of friction could be calculated at any location on the die surface. The schematic in Figure 12 illustrates the operating principle of this slidometer design.

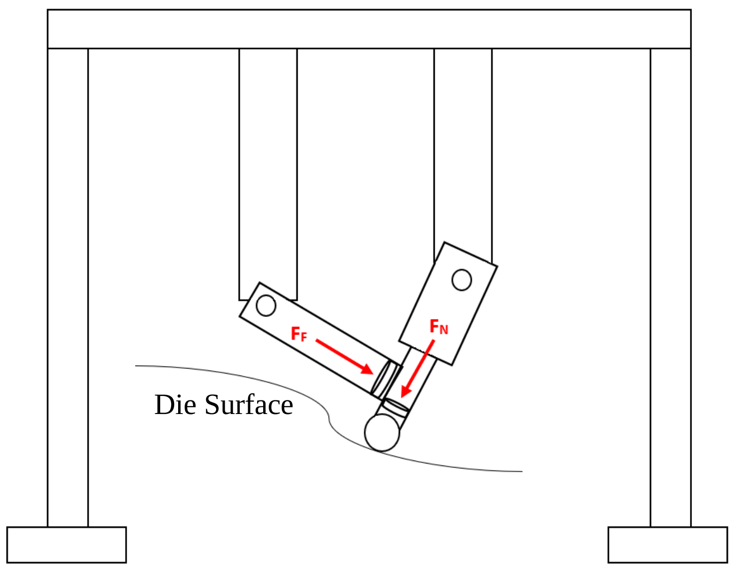


Figure 12. Schematic of Slidometer Design 1

The design shown in Figure 12 is intended to be a portable slidometer that can be used to measure the friction at different locations on the die surface. To properly simulate the sheet metal forming process, this slidometer was designed to have a small piece of sheet metal around a roller at the end of the cylinder with applied force F_N. This would ensure that the friction conditions measured were equivalent to those that would occur during the sheet metal forming process.

Using legs of adjustable height, this slidometer could be leveled at any number of locations on the die surface. Two perpendicular forces, F_F and F_N would be applied using spring driven cylinders.

By attaching the two cylinders perpendicular to each other using bolts, the coefficient of friction could be easily determined as the ratio between the friction force F_F and the normal force F_N. The cylinders could be moved vertically and held in position using screws. Clevis pins would allow for rotation at the joints to ensure that the two cylinders could be moved individually to ensure they would remain normal to one another. The values for these two forces would be measured using two different load cells.

To determine the friction most accurately during sheet metal forming, the coefficient of friction at the point of slippage must be determined. Since the slippage point is where friction transitions between static and kinetic friction, this is the point at which the coefficient of friction is maximized. Therefore, by applying a constant normal force F_N and steadily increasing the friction force F_F until the sheet metal covered tip slips against the die surface gives the necessary values to calculate the coefficient of friction. The force values recorded by the two load cells could be used to calculate the coefficient of friction as a function of time. Using this data, the maximum coefficient of friction value could be determined at a given location on the die surface. Figure 13 depicts a theoretical plot of the coefficient of friction as a function of time, like what would be expected using this slidometer design.

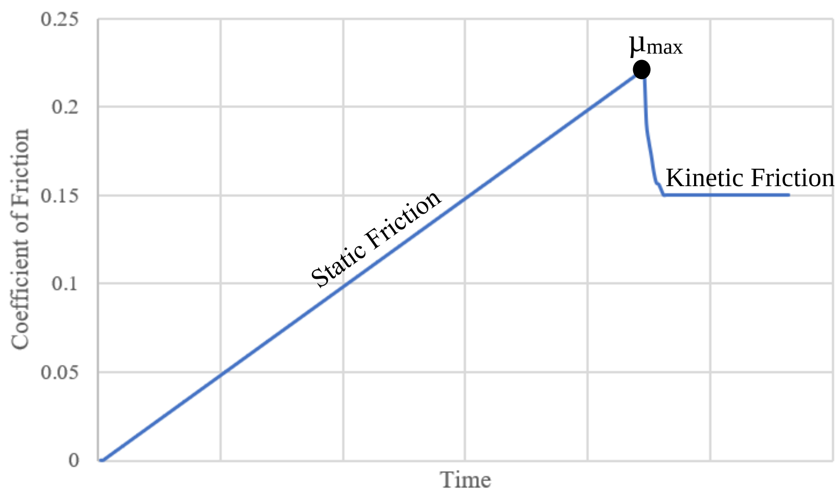
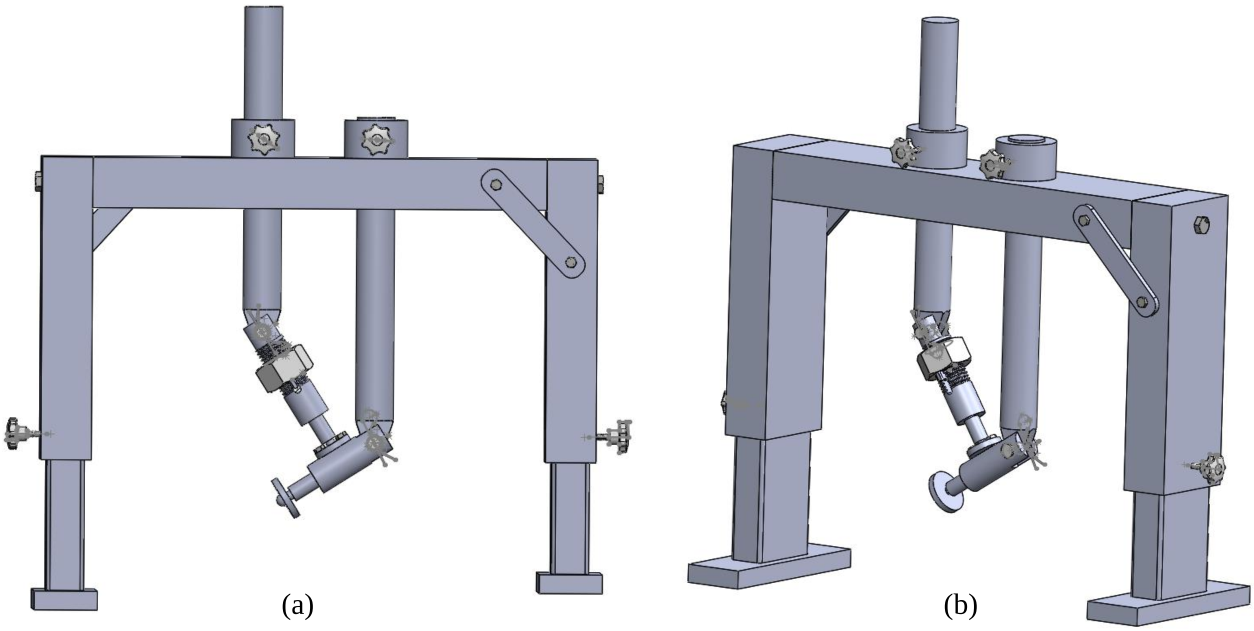


Figure 13. Theoretical Coefficient of Friction

Using the schematic provided in Figure 12, a CAD model was created of the slidometer, as can be seen in Figure 14.



(a) (b)

Figure 14. Side View (a) and Isometric View (b) of CAD Model of Slidometer Design 1

The CAD model of the slidometer created in design 1 illustrates the overall operation of this design. Using a given die surface on which a piece of sheet metal is to be formed, this slidometer can be adjusted such that the tip covered in sheet metal contacts the die surface at an angle normal to the surface. Both legs of this slidometer are adjustable in height, allowing the tip to come close to contact. Additional alignment of the tip is performed by sliding the two long cylinders vertically and holding them in place with two grips attached to M6 x 1 mm studs. Clevis pins on each of these cylinders ensure that they remain perpendicular to each other. Once the tip covered in sheet metal is aligned with the die surface, the friction force and normal force are applied using springs. A close-up of the operation of these pistons is seen in Figure 15.

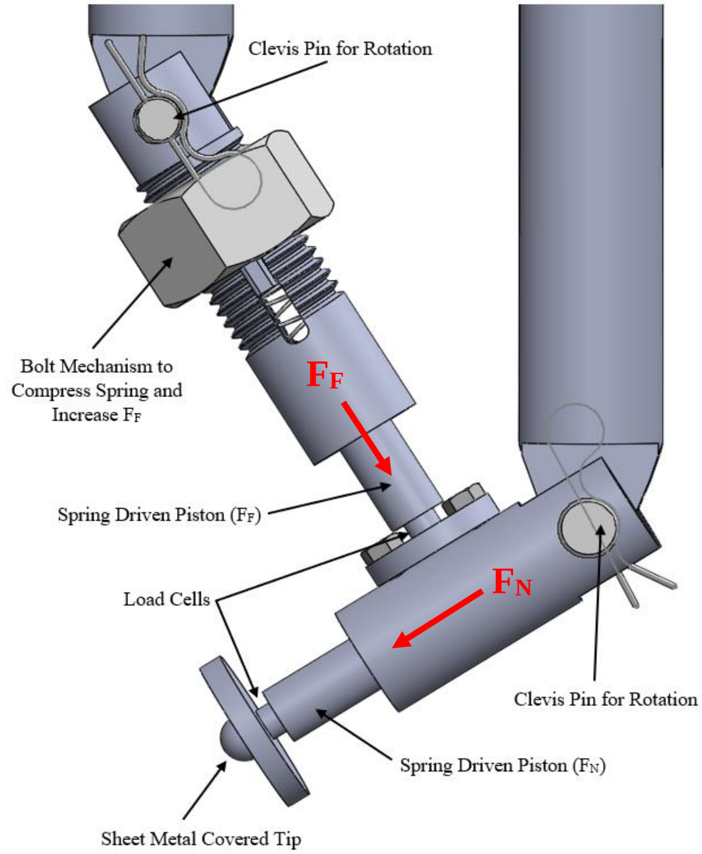


Figure 15. Close-Up of Pistons in CAD Model of Slidometer Design 1

As seen in Figure 15, the two cylinders are bolted together to ensure that the applied forces F_N and F_F remain perpendicular to one another. The piston on the right-hand side contains a 0.48 in. OD spring with a stiffness of 10.5 lbs./inch. This spring has a maximum load of 5.57 lbs. and is used to apply a constant force F_N to the sheet metal covered tip. At the same time, the piston on the left uses an equivalent spring to apply a force F_F. Using a 1¼"-7 nut of outer diameter $1^7/_8$", an aluminum bar is used to compress the spring. This nut is screwed down until the force applied by the spring exceeds the friction between the die and sheet metal, causing the tip to slip against the die surface.

The two LCM100 Threaded In-Line Load Cells record these forces and export the data via USB to a recording software. Using these experimental values, the coefficient of friction is calculated for each changing value of F_F. As a result, the coefficient of friction at the slippage point is known for different locations on the die surface.

A Bill of Materials for this design can be seen in Table 1. However, this does not account for machining costs of the necessary parts. The following parts need to be machined for this design: frame, cylinders, corner braces, rod for compressing spring, tip for sheet metal, load cell holders. Some of these parts may be able to be purchased and modified to fit this slidometer design, but this will significantly increase the production cost for this slidometer.

Table 1. BOM for Slidometer Design 1

Item	Quantity	Cost
LCM100 Futek Load Cell	2	$750.00 (each)
Precision Compression Spring	2	$5.03 (3-pack)
Plastic Knob w/ 7 Arm Grip	4	$3.31 (each)
Carbon Steel Clevis Pin	2	$7.18 (5-pack)
1.25 x 7” Nut	1	$4.51 (each)
M6 x 1 mm Bolts	6	$6.44 (50-pack)
M10 x 1.5 mm Bolts	2	$11.44 (10-pack)
Total Cost: $ 1547.84		

The slidometer described in design 1 has several benefits to using it. First of all, the design makes it easy to use on a variety of different die surfaces. Since this slidometer is designed to measure friction on the surface of a die and can be moved to the die location with relative ease, it can be used to measure friction at different locations on the die surface. Furthermore, sheet metal pieces are applied to the tip of a roller in this design, making it easy to change the type of sheet metal being tested. The combination of these two factors makes it easy for this slidometer to be used to measure friction in many different sheet metal and die combinations. Additionally, different amounts of lubrication can be added at a given test location on the die surface, meaning that this slidometer can provide experimental data on the effects of lubrication on friction between the sheet metal and die surface.

However, this design is limited in its ability to give a fully accurate depiction of friction in the sheet metal forming process. The main limitation is that this design does not allow for measurement of friction during the actual sheet metal forming process. It does allow the coefficient of friction to be calculated at different locations along a die surface where sheet metal will be formed, yet it cannot be utilized in the actual process. This is a significant limitation because the testing conditions will not be equivalent to the conditions under which the sheet metal is formed. The coefficient of friction measured by this slidometer may not be as accurate. Since an accurate coefficient of friction is necessary in the simulation of sheet metal forming, this limits the usefulness of this slidometer design. Further limitations of this slidometer include that it is expensive to make and it is a bulky design.

Based on the limitations of the first slidometer design, a second slidometer concept was designed to measure friction in the metal forming process, as detailed below.

Design 2

In the second design, a slidometer was created to be used alongside a drawbead simulator to better understand how friction changes during the sheet metal forming process. In this design, the friction is measured using a drawbead test, as described above. Rather than measuring friction at specific locations on a die like the slidometer described in design 1, this slidometer would be able to determine the friction more accurately during the deformation of a piece of sheet metal. The concept behind this slidometer design is seen in Figure 16.

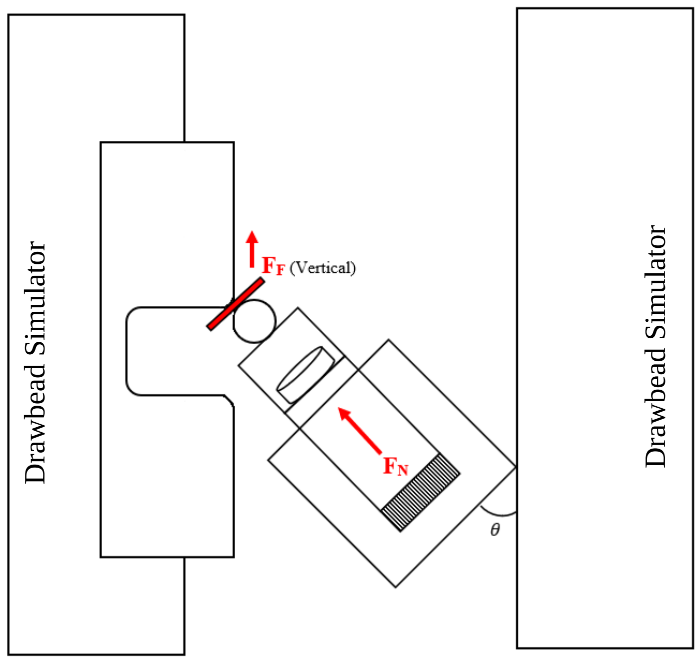
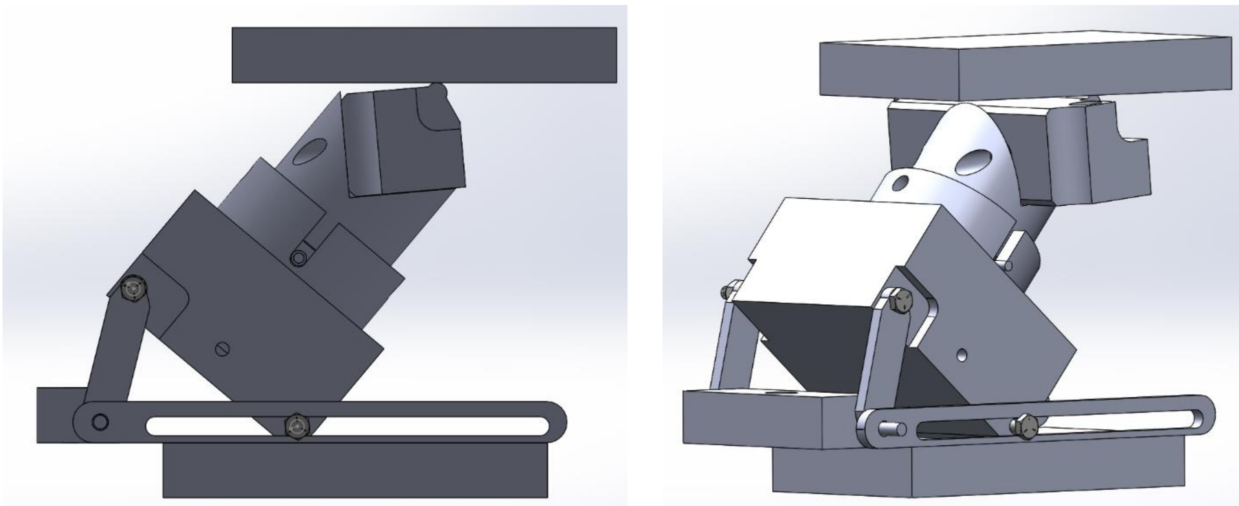


Figure 16. Schematic of Slidometer Design 2

As seen in Figure 16, the slidometer concept developed in design 2 fits inside of a drawbead simulator. In this design, an Instron Tensile machine is used to pull a strip of sheet metal vertically between two drawbead inserts. The force measured by the Instron is the force necessary to overcome the friction between the sheet metal and drawbead insert, or F_F. A perpendicular force F_N is applied using a piston and measured by a load cell placed inside of the slidometer design. To ensure that the F_F and F_N are perpendicular to one another, the angle between the slidometer and the drawbead simulator can be changed. Furthermore, a roller is used between the piston and sheet metal piece so that the only friction in this setup is between the sheet metal and drawbead insert.

Using the schematic from above, a CAD model was created of this slidometer design, as seen in Figure 17.



(a) (b)

Figure 17. Side View (a) and Isometric View (b) of CAD Model of Slidometer Design 2

In this design, the force is applied to the sheet metal piece using a hydraulic cylinder. This cylinder is designed to push the roller against a piece of sheet metal such that the contact point at the tip of the roller is perpendicular to the edge of the drawbead insert. An exploded view of the roller, roller holder, and piston can be seen in Figure 18.

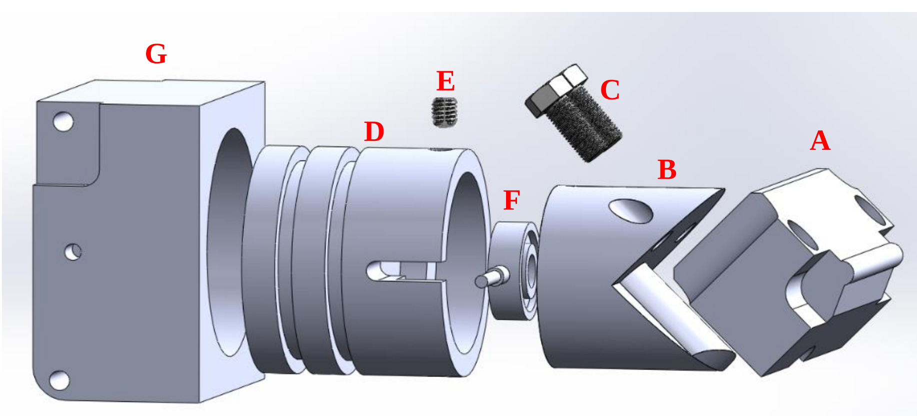


Figure 18. Exploded View of Piston in Slidometer Design 2

In slidometer design 2, a hydraulic piston is used to apply a measurable normal force to a sheet metal strip. In this design, the roller (A) is attached to a machined roller holder (B) using two 7/16”-20 bolts (C). This roller holder is designed to slide inside of a piston (D) and is held in place using a set screw (E). A Futek LTH350 load cell (F) is placed between the roller holder and the bottom of the piston to obtain measurements of the force applied by the piston. The hydraulic piston is sealed using two U-cup seals rated to withstand pressures up to 250 psi. This piston slides into the cylinder (G) which has a threaded hole drilled into the side to route hydraulic fluid into it.

This assembly is arranged inside of the drawbead simulator such that the hydraulic fluid can be pumped into the cylinder without the tubing being pinched. Furthermore, the USB cable for the load cell is routed in the same direction as the hydraulic tubing to ensure that force measurements are accurately recorded.

One of the primary attributes of this slidometer design is that the angle between the slidometer and drawbead simulator, θ in Figure 16, can be changed to allow the tip of the roller to be at an angle perpendicular to the surface against which the sheet metal strip is placed. To do this, the slidometer design has a rail system to change this angle, as seen in Figure 19.

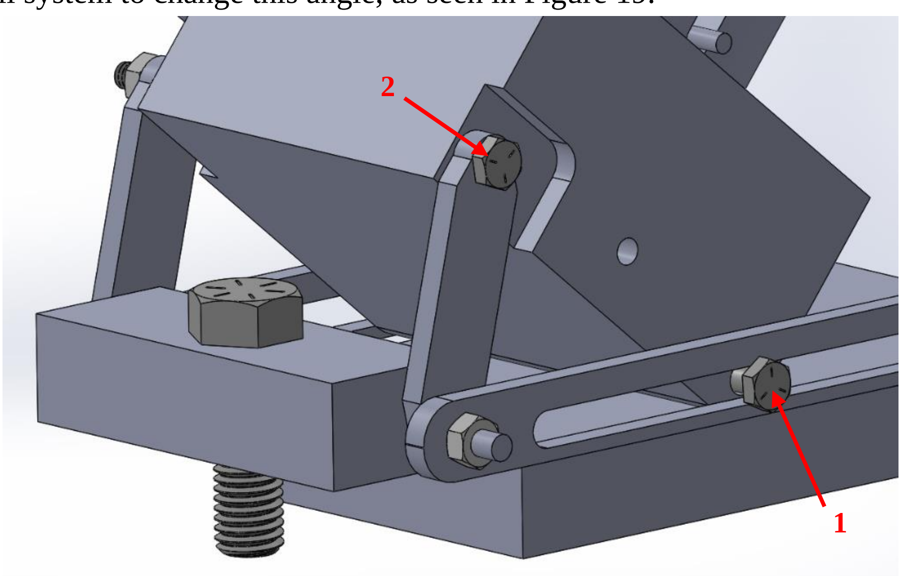


Figure 19. View of Angle Adjuster in Slidometer Design 2

This slidometer design has two different rotation points to adjust the angle at which the roller tip contacts the sheet metal strip. The ¼”-20 bolt at point 1 in Figure 19 can be loosened using a nut on the opposite side of the cylinder. This allows the lower corner of the cylinder to slide along the rail. By tightening the nut on the opposite side, the angle of the roller and piston can be fixed. Another ¼”-20 bolt is located at point 2 in Figure 19, which allows the opposite corner of the cylinder to pivot to allow the cylinder to slide along the rail. Lastly, a 5/8”-11 bolt is used to secure the slidometer to the drawbead simulator.

Placing this slidometer between the drawbead simulators would allow for the coefficient of friction to be measured as the sheet metal strip is pulled through the drawbead insert. In doing so, the friction force, F_F, can be measured and recorded by the Instron machine. At the same time, the normal force, F_N, would be recorded by the LTH350 load cell packaged inside the slidometer. Using the ratio of these two forces, the coefficient of friction could be determined during this test.

A Bill of Materials for slidometer design 2 can be seen in Table 2. Once again, this does not account for the parts that need to be machined including the hydraulic cylinder, piston, roller holder, rails, and attachment block. The machining of these parts will significantly increase the total cost of production.

Table 2. BOM for Slidometer Design 2

Item	Quantity	Cost
LTH350 Futek Load Cell	1	$750.00
¼”-20 Steel Bolt (5.5” Long)	2	$10.48 (10-pack)
¼”-20 Steel Nut	4	$4.88 (100-pack)
5/8”-11 Steel Bolt (2” Long)	1	$12.45 (10-pack)
7/16”-20 Steel Bolt (1” Long)	2	$12.27 (25-pack)
3/8”-16 Set Screw	2	$7.94 (50-pack)
3” ID U-Cup Seals	2	$8.04 (each)
Roller	1	Supplied by OU
Hydraulic Fluid	1 qt.	Supplied by OU
Tee Fitting	1	Supplied by OU
¼” OD Hydraulic Tubing	5 ft.	Supplied by OU
Electric Pump	1	Supplied by OU
Total Cost: $814.10		

The primary benefit of slidometer design 2 is its ability to measure the coefficient of friction during an actual drawbead simulator test. In doing so, a more accurate analysis of the friction conditions during sheet metal forming can be understood. This slidometer allows for a more thorough understanding of how the friction changes during the sheet metal forming process. Realistic forces for sheet metal forming can be used in the testing of this slidometer, which makes it easier to understand the correlation between the coefficient of friction and the applied force. Furthermore, this slidometer setup can account for changing speed and load conditions during the sheet metal forming process. Not only does this provide a better understanding of how friction changes with these parameters, but it makes it possible to study these variables to find an optimal speed and load for sheet metal forming. This slidometer also allows for different forms and amounts of lubrication to be tested to determine how to best utilize lubrication to reduce friction. Different sheet metal strips and drawbead inserts can be used with this slidometer to analyze friction that is present in different sheet metal forming conditions.

However, this slidometer is limited by several factors. The cost to make this slidometer is one limitation to its ease of development and use to measure friction. In addition, the design is slightly cumbersome to setup. Getting the slidometer arranged so that it applies a force perpendicular to the sheet metal strip may be difficult, especially in the limited space in the drawbead simulator. Furthermore, the attachment and placement of the parts used in the hydraulic system to apply pressure must be considered in setup. This slidometer is designed for alignment of the hydraulic tubing to ensure it does not interfere with the movement of the drawbead simulator, but caution must be taken so that there is no interference between components. Lastly, using a hydraulic cylinder to apply the friction force against the sheet metal strip introduces a risk of leaking and failure. However, the U-cup seals included in this slidometer are designed to prevent this from occurring.

Summary/Conclusions

The sheet metal forming process is a complicated process involving many different variables. Through an initial study of this metal forming process, a thorough understanding of the factors influencing the sheet metal forming was developed. Common testing methods for measuring friction in sheet metal forming were studied to understand how the following parameters influence friction in sheet metal forming: material properties, forming conditions, lubrication, surface roughness, and punch and die radii. Several existing slidometers were studied to understand current methods to measure friction.

To better understand the complex effects of friction during the sheet metal forming process, two slidometer designs were created. Both designs were created with the intent of being used in different ways to measure friction, and an analysis of both designs was performed for comparison purposes.

Since sheet metal forming is a reliable, cost-effective method of metal forming, developing accurate simulations of this process is important. To have better development techniques and part quality, the effects of friction must be known. For this cause further research and development will continue to develop a better model to accurately analyze friction in sheet metal forming. In doing so, the effects of friction will be better understood, leading to more cost-effective sheet metal forming procedures with improved part quality and increased tool life.

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