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TRIBOLOGICAL IN METAL FORMING PROCESS AND THE USE OF BIO LUBRICANT AS METAL FORMING LUBRICANT: A REVIEW

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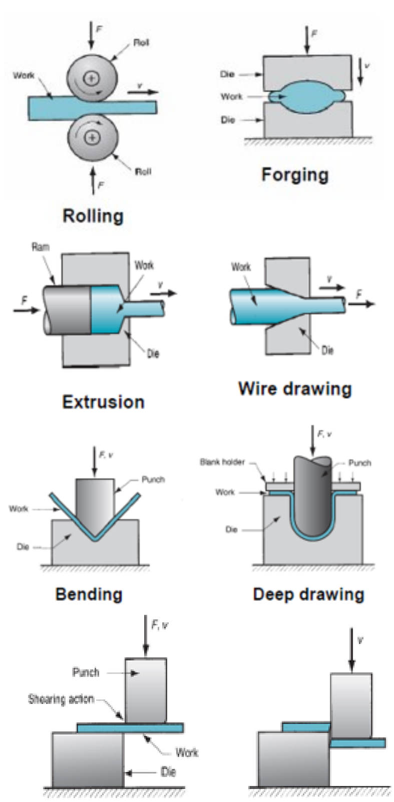
Graphical abstract



Abstract

Due to its low scrap, high production rates, and higher yield strength of cold-formed products following forming operation, cold metal forming methods stand out as the most beneficial method of metal forming. The use of metal forming process is one of the major aspects in manufacturing process and the utilised of lubricant is extremely vital. When referring to lubricants, the term "bio-lubricant" refers to a stock that is both renewable and biodegradable. Fats and oils, which are derived from fatty acids, may be reacted with alcohols to create esters. It is crucial for the economy, people, and the environment that lubricants be developed and used efficiently. For this article, we scoured the literature and analyzed the most up-to-date research on the topic of metal forming process improvement and the use of vegetable oil as a metal forming lubricant. This research intends as a case study and demonstrating the tribological analysis in metal forming process and the potential of using bio lubricant in the metal forming. Future manufacture of new oil blends from new and conventional oil sources will be offered to the market for a variety of economic and health concerns.

Keywords: Bio-lubricants; metal forming; vegetable oil; cold forging; friction

Abstrak

Oleh kerana sisa yang rendah, kadar pengeluaran yang tinggi, dan kekuatan hasil yang lebih tinggi daripada produk yang dibentuk sejuk selepas operasi pembentukan, kaedah pembentukan logam sejuk menonjol sebagai kaedah pembentukan logam yang paling bermanfaat. Penggunaan proses pembentukan logam adalah salah satu aspek utama dalam proses pembuatan dan penggunaan pelincir sangat penting. Apabila merujuk kepada pelincir, istilah 'pelincir bio' merujuk kepada stok yang boleh diperbaharui dan boleh terurai secara biologi. Lemak dan minyak, yang berasal dari asid lemak, boleh bertindak balas dengan alkohol untuk membentuk ester. Adalah penting untuk ekonomi, orang, dan alam sekitar bahawa pelincir dibangunkan dan digunakan dengan cekap. Untuk artikel ini, kami menyemak literatur dan menganalisis penyelidikan terkini mengenai topik peningkatan proses pembentukan logam dan penggunaan minyak nabati sebagai pelincir pembentukan logam. Penyelidikan ini bertujuan sebagai kajian kes dan menunjukkan analisis tribologi dalam proses pembentuk logam dan potensi penggunaan bio lubricant dalam pembentukan logam. Pembuatan masa depan campuran minyak baru dari sumber minyak baru dan konvensional akan ditawarkan kepada pasaran untuk pelbagai masalah ekonomi dan kesihatan.

Kata kunci: Pelincir bio; pembentukan logam; minyak tumbuhan; penempaan sejuk; geseran

1.0 INTRODUCTION

According to DIN 8580 from the German Institute for Standardization, metal forming is the "manufacturing by plastic (permanent) alteration of the shape of a solid body while retaining both its weight and its cohesiveness". Depending on the forming mechanism (tensile, compressive, bending effect, by shearing), part to be formed (bulk, sheet), time dependence (time independent and dependent processes like extrusion and upsetting), or forming temperature, metal forming processes can be broken down into several distinct categories (cold, warm, hot forming). The metal may be softer and more malleable when hot formed, and recrystallization can help when cold formed, yet strain hardening can increase the strength of a cold-formed product. By eliminating thermal issues like oxidation and deformation, cold forming may also allow for greater geometric precision and surface polish.

Forging is a common manufacturing process because it can be used for both high-volume manufacturing and the creation of prototypes [1]. Forging is used in a wide range of industries to create a wide range of components, including balls for rolling bearings, small bolts, pins, gears, cam and crankshafts, shafts, axles, holding hooks, flanges, hand tools, aircraft landing structures, turbine blades, some components of medical instrument like surgery blades, etc. The need for micro-components has been on the rise in a wide variety of sectors recently. Making these kinds of intricate components requires the advancement of micro-manufacturing techniques, making this a critical concern. Metal forming is a potential method of producing metallic components because to its advantageous features, such as high productivity, cheap cost, and excellent quality of the formed parts [2]. Over the last two decades, researchers have dedicated a great deal of time and energy to studying the size influence on deformation behaviours in the forming process and improving the process across the board. Having a comprehensive understanding of these studies is crucial for advancing metal forming as a means of supporting component design and development and for bringing this micro-manufacturing technique into the industrial world [3]. Some researchers have started to combine numerical analysis with experimental research. Finite element method is very helpful way to help the researcher in predicting what will happen under very extreme condition.

Closed die forging is the main metal forming process for the mass-production of middle-size or small forging parts [4]. Defining the material's behaviour in reaction to process factors including billet shape, final forged component shape, and applied stress is crucial considering the mechanical nature of the deformation in the closed die forging process. In addition, controlling process parameters so that, the optimum product is obtained, are the goal of the manufacturing operation. Closed die forging processes, in contrast to other types of forging process, may create a large number of unique components. Because the direction of material flow and the atomic structure of the material can be regulated, forged components are robust and durable. As a result, forgings are a reliable option for demanding and essential uses [3][4].

Process factors, such as die shape and material behavior during deformation, as well as friction, and material flow properties in a mold cavity, are crucial in proposed design. It is also crucial to choose the right die materials, temperature, speed, lubrication, and machinery. There has been a significant rise in the use of Design software systems in all stages of the forging production process [5]. Finite element techniques in conjunction with validation methods (such as mathematical validation, backward tracing, artificial intelligence, experimental validation and automatic control algorithm) are used to simulate and validate metal forming process. In order to find an optimal die or billet shape, mathematical validation has been predominant [6]. Validation techniques are utilized to optimize forging process for a certain objective function to improve the product quality and save power, material, time and cost. This study used a finite element approach to simulate the forging process, with the goal of better comprehend the friction, metal flow of the palm oil lubricant and the stress-strain distribution in the forged product. Besides that, this research also to analyses the process in terms of its independent and dependent factors.

The use of vegetable oil as a lubricant was of growing interest in the industrial sector [7]. This is due to the fact that natural oils and fats were approved for use in the food, lubricant, and biodiesel industries due to their unique chemical characteristics and properties [8]. Green chemistry and the use of renewable raw materials have a bright future, and the use of environmentally friendly lubricants will play a crucial part in both of these fields. In general, vegetable oil has characteristics that are quite distinctive, offering a variety of options accessible in conventional petrochemistry [9]. Using vegetable oil as a lubricant in internal combustion engines has been shown to have the potential to lower carbon monoxide and hydrocarbon emissions [10].

The concern over the environmental impact of using petroleum-based products has grown in conjunction with the rate of mineral oil resource depletion around the world [13]. The petroleum base stocks used in most industrial lubricants today make them harmful to the environment and make it difficult to dispose of the products. Because vegetable oils with a high melting point are not simple organic compounds, the sample's consistency at any given temperature might range from completely solid to completely liquid to a mixture of the two [12-13].

Vegetable oils are flexible lubricants that have seen extensive application. High-oleic vegetable oils are a viable alternative to traditional mineral oil-based lubricants and synthetic esters [14]. Using vegetable oil as an automotive lubricant is a step in the right direction since it is inexpensive, clean, sustainable, biodegradable, non-toxic, and ecologically beneficial [15].

In conclusion, the metal forming process is one of the vital areas to research, and the presence of lubricant is essential for the process. However, compared to the study on its usage as an engine oil, the investigation on the use of bio lubricant in metal forming is still in its infancy. This review discusses type, tribological analysis, and the usage of bio lubricant in the metal forming process in comprehensive manner.

2.0 METAL FORMING

Metal forming is a large set of manufacturing processes in which the material is deformed plastically to take the shape of the die geometry. The tools used for such deformation are called die, punch etc. depending on the type of process. The first manufacturing forging process which using people to produce tools, utensil as weapon is estimated about 7000 BC as mention by Canter., [16]. There are a few types of metal forming that is bulk deformation [17] and sheet metal working [18] as shown in Figure 1. Common application of metal forming product are component for automobile, machine tools, construction, transportation and many more.

Nowadays, metal forming processes may be used to a wide variety of materials, including ceramics and polymers. The industry's rapid evolution has resulted in a simpler, quicker, and more consistently cutting-edge procedure. A recent improvement to the fabrication department of Atlas Manufacturing, a precision sheet metal fabricator and stamper in the United States, was the adoption of many new laser and CNC punch equipment. As a means of increasing the stamping division's speed and adaptability, they concentrated on shortening the amount of time it takes to switch between dies. Because of this situation, it develops new products and hand tools that reduce die-swap times by 50-70%. The efficiency of the worker also will be increase as they can focus into making many parts with less setup time [19].

Taking into consideration One of the most well-known methods for creating metals is forging, it was started by using hammer and anvil, though introducing water power to the production and working of iron in the 12th century allowed the use of large trip hammers or power hammers that exponentially increased the amount and size of iron that could be produced and forged easily [20]. Afterward, as the technology advanced forging is used to produce cannon and rifle parts. Today, forging is used in different industries for the manufacturing of variety parts such balls for rolling bearings, small bolts, pins as well as gears, cam and crankshafts, shafts, axles, holding hooks, flanges, hand tools aircraft landing structures, turbine blades, some medical instrument components such as surgery blades etc. As in metal forming there are different classifications for forging such as in terms of temperature (hot, isothermal, warm and cold forging) [21], die (open, closed-die) [22], shape (compact shapes, disk shapes, long shapes) [23]. Figure 2 shows the typical of bulk deformation and sheet metal working that been used in the industry.

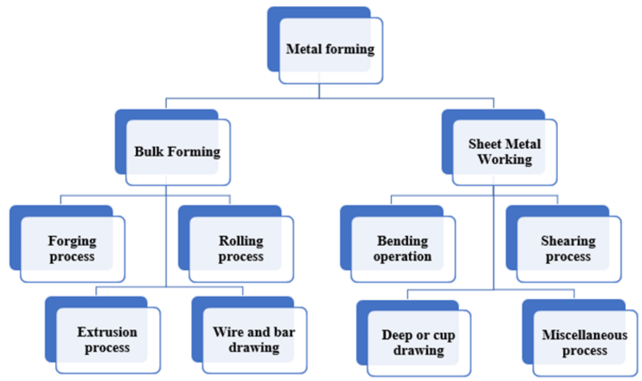


Figure 1 General classification of metal forming [24]

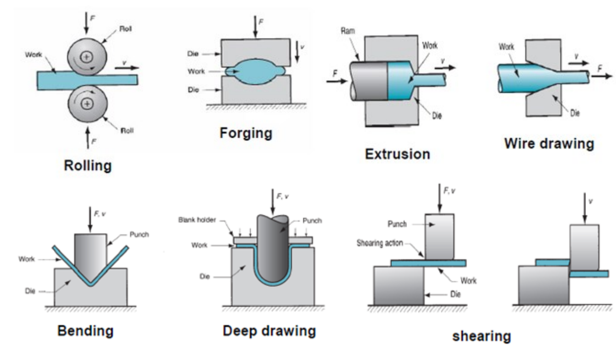


Figure 2 Example of bulk deformation and sheet metal working [25]

Figure 3 illustrate the general forging process which consist top die bottom die and billet at the middle between both die. Forging is the process where the work piece (billet) is compressed inside the chamber to form the desired shape through the die [26-27]. The finishing product will strictly form according to the die pattern. As mention earlier forging has two type of process that is cold forging and also hot forging.

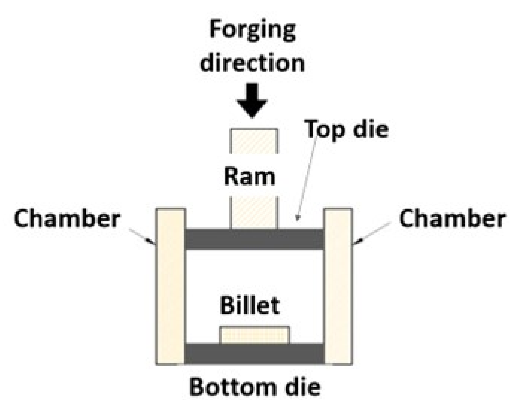


Figure 3 General Forging process

2.1 Classification of Operation

Forging and extrusion are the two main processes that are frequently used in the development of lubricants while studying the tribological performance of metal forming processes. Cold forming process is strongly advised for lubricants with low melting point since low temperature metal forming procedures do not necessitate heating the material.

2.1.1 Forging Process

The forging process results in separate components being produced. It is possible to regulate the flow of metal and the grain structure, resulting in components with excellent mechanical characteristics (higher strength and toughness). As a result, they may be utilized with reliability in high-stress and sensitive applications. Open die forging, impression die forging, and closed die forging are the three primary types of forging.

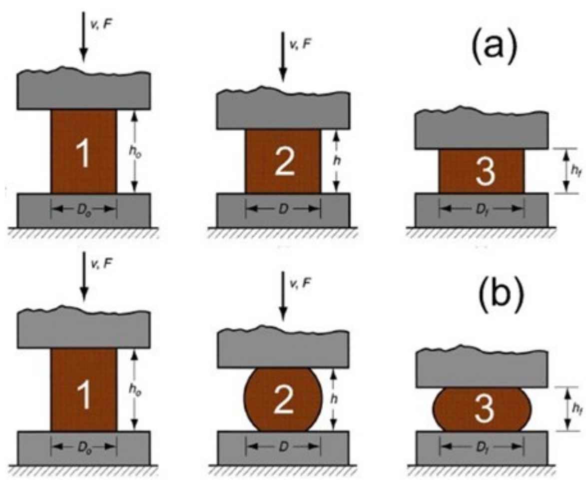


Figure 4 Open Die Forging (a) Ideal with no Friction (b) with Friction [28]

As seen in Figure 4, open die forging normally entails inserting a solid cylindrical workpiece between two flat dies and compressing it to reduce its height [28]. This process is commonly referred to a simple upsetting. Under ideal condition, a solid cylinder deforms as shown in Figure 4(a). In reality, the specimen takes on the form of a barrel, as seen in Figure 4(b). In most cases, barreling is generated by friction forces at the die-workpiece interfaces, which act to prevent the outward flow of material at these interfaces from occurring.

The workpiece acquires the form of the die cavities (impression) as it is being agitated between the closing dies in closed-die forging. A typical example is shown in Figure 5, where some of the material flows radially outwards and forms flash [28]. A significant level of pressure is applied to the flash as a result of its large length to thickness ratio. These pressures in turn mean high friction resistance to material flow in the radial direction in the flash gap. Because high friction encourages the filling of the die cavities, the flash has a significant role in the flow of material in impression die forging.

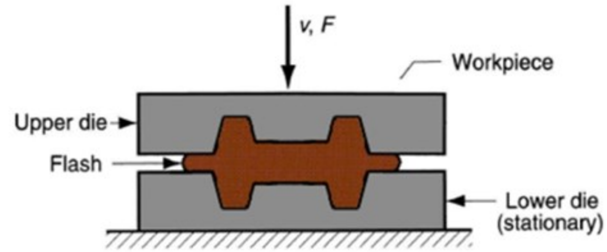


Figure 5 Closed Die Forging [28]

Because dies have a significant impact on the quality of the finished product, extra attention must be given during the design of the dies and the selection of the die materials. As seen in Figure 6, close die forging necessitates larger forging loads, it means that forging equipment with a larger capacity than other forging techniques is required.

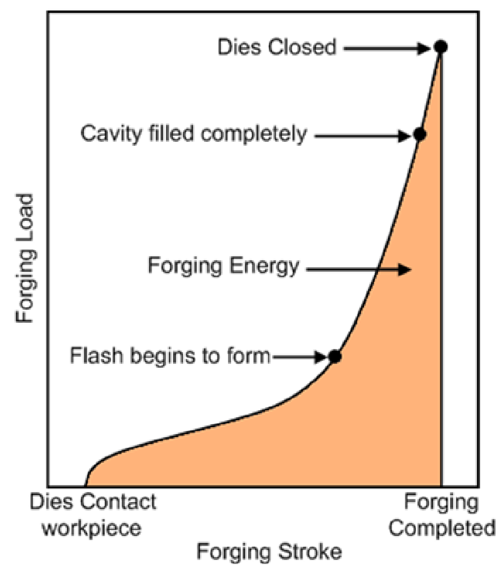


Figure 6 Typical Load Displacement Curve for Closed Die Forging [28]

2.1.2 Extrusion Process

Extrusion began with the extrusion of main pipes in the nineteenth century and was regarded as a newbie in the industry, despite the fact that it is one of the most well-known metal forming techniques. This is due to the fact that the extrusion chamber could not have been correctly developed before 1930 in order to withstand the high temperature and pressure required for the extrusion process of steels. It is now frequently used for both metals and polymers. Railings for sliding doors, window frames, aluminum ladder frames, rods, tubes, and numerous other solid and hollow parts are examples of often extruded metal products. Extrusion of plastics can also produce sheets, films, and wire coatings.

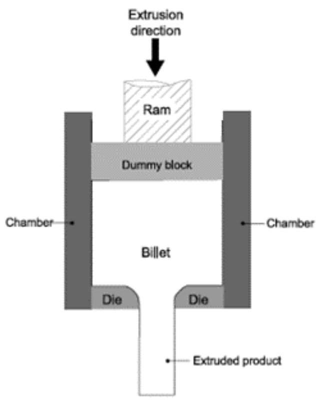
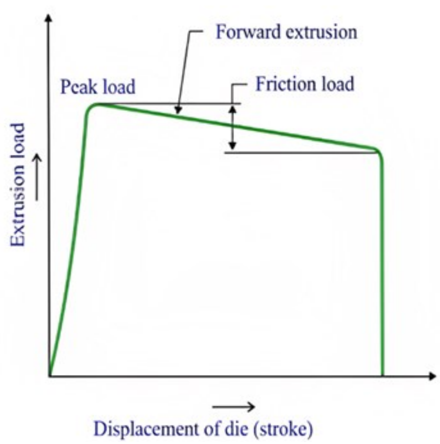


Figure 7 General extrusion process

The general extrusion process, which has a chamber, die, ram, dummy block, and billet as its main components, is clearly shown in Figure 7. Workpieces are forced through a die during the extrusion process [98]. One long continuous product was generated from the extruded material, which will closely resemble the die pattern. Extrusion is a continuous operation, and the finished product, also known as extrudate, is then trimmed to the necessary lengths. Figure 8 shows the typical extrusion load where the pattern is very different from the forging process where the load has a steady state region.



Forging 8 Punch load versus punch displacement curves in forward rod extrusion [127]

Despite the cold extrusion technique requiring higher loads, more expensive lubrication, simpler shapes, and less deformation, more benefits were found. The extruded item will get stronger and harder due to a strain hardening action. Additionally, it is crucial to generate metal components through cold forming if you want to create the directional strength attribute that is brought on by the direction of the grain in the metal. Additionally, accurate production of geometric tolerances and net-shaped features is also possible with a superior surface polish [30]. Researchers studied the cold extrusion technique in area of specialization is the cold extrusion. They tested it using a variety of industrial lubricants, including mineral oil-based ones and alternative lubricants like wheat flour, powdered soap, vegetable oil, and palm oil [30][36].

2.2 Tribological in Metal Forming

2.2.1 Friction in Metal Forming

The term "friction" is often used to describe the force that opposes the motion of two or more sliding objects. There are two types of friction that occur naturally in the world: dry surface friction and lubricated surface friction [29]. Friction and lubrication play critical roles in several manufacturing processes, including forging, sheet metal forming, rolling, and extrusion. In metal-forming operations, friction influences both the forming forces and the stability of the deformed workpiece. A number of investigations on the role of stress in various stages of development have been undertaken [30-32]. Examination often focused on how to determine the friction coefficient. Today, the finite element approach is the basis for a wide variety of computer programmes used in industry with the goal of optimizing the metal-forming process. Lack of information about the precise numerical value of the contact friction coefficient, however, may drastically restrict the accuracy of such research. Evidence from a number of research suggests that the coefficient of friction may be calculated using just data regarding the typical material flow during a deformation phase [33]. Subsequently, this information offers expertise to automate a process and to design an effective die to avoid material defects and failures during a deformation phase.

Schroeder and Webster [34], conducted a series of compression experiments of aluminum and magnesium disks under different disc conditions in an early study. Schroeder subsequently developed experimental friction curves from the dimensional ratio of the pressure applied to the flow stress to the ratio of the compressed surface radius to the deformed surface thickness. The coefficient of friction for different disc conditions can be estimated by matching the experimental curves with theoretical curves. Although it is believed that their findings had to be validated, this approach was a useful method to measure the friction coefficient for the metal forming process. In many later investigations, Schroeder's studies were continued [35-37]. The authors generally agreed that the friction coefficient could be estimated by using the knowledge of material flow characteristics for a large deformation of plastics, but the applicability of this approach was limited to a maximum limit of the friction value coefficient that could be calculated [38].

This technique of disk compression is considered a difficult method to perform in practice, since direct force measurement, knowledge of material properties and a special measuring tool are needed if the investigation is carried out at a high temperature. This method was therefore modified in an attempt to estimate the coefficient of friction for processes of metal forming [39-40], by following the same material flow characteristic theory but by modifying the specimen from cylindrical to ring geometry. This testing method was later referred as the test for ring compression.

Amontons, [41] made the most detailed approach to the modem ideas on friction about hundred years ago. Almost a century later, Coulomb, [42] largely established the basic laws of friction and while recognizing that adhesion could play a part in friction, he considered the interaction of surface roughness to be the major factor. Tabor, [43] provided the general vital picture of the current understanding of the frictional mechanism. Tabor has illustrated three fundamental elements involved in the sliding motion of unlubricated solids:

1) The real contact area between the rough surfaces
2) Form and strength of the bond formed at the contact interface
3) The way in which the material in and around the contacting regions is sheared and ruptured during sliding

From the definition of the friction coefficient, it is easy to understand the importance of these three elements;

$$\mu = \frac{Q}{F} \tag{1}$$

Where;
Q - Tangential force needed to shear the junction between the contacting surfaces
F - External normal force.

The actual contact load, *P*, in the true area of contact is different from *F* by the amount of the intermolecular forces acting between the surfaces in contact. These forces are referred to as adhesion forces, F_s, and hence.

$$P = F + F_s \tag{2}$$

$$\mu = \frac{Q}{F + F_s} \tag{3}$$

Via the broader issue of contacting rough surfaces, the contact load, *P*, is connected to the actual area of contact. F_s, or adhesion force, measures how strongly two surfaces are stuck together at an interface [44].

In metalworking theory, slip boundary conditions have several forms. They are constant kinds of friction and are referred to as the Coulombic and Tresca parameters, respectively [45-46]. For the case of a Coulombic boundary condition, it is assumed that the frictional shear stress, *τ*, is directly proportional to the normal stress, *p*. The adherence results in the presence of adequate lubricant, the effect of adhesion, F_s in equation (3) can be neglected, therefore, these are referred to as the parameters Coulombic and Tresca, also known as constant forms of friction.

$$\tau = \mu P \tag{4}$$

However, in metal forming processes, the interface pressure, *p*, can reach a multiple of the yield strength of material. Thus, the linear relationship between τ_f and *P* in -Coulomb's model is not valid at high contact pressure levels because the shear stress, τ_f, cannot exceed the shear strength, *k*, of the deformed material that is normally workpiece. Therefore, the coefficient of friction becomes meaningless when *μp* exceeds *τf*. Thus, to avoid this limitation of Coulomb's model, the shear friction model was proposed by Orowan [47]. In this model, as shown in Figure 9, the frictional shear stress, τ_f, at low pressure is proportional to the normal pressure such as Coulomb's model, however it equals to the shear strength, *k*, at high pressure.

For a cylindrical specimen subjected to uniaxial deformation, the values of *τ* and *P* would typically be derived from the radial coordinate, *r*, which is centered on the axis of the specimen. The Tresca boundary condition, in contrast, defines the wall traction as being some function of shear flow stress, τ_f , thus

$$\tau = m\tau_f \tag{5}$$

Where, m is known as the interface shear or the friction factor.

The least value in the fully lubricated case where the normal wall stress induces plastic flow is given as the uniaxial yield stress, σ_y or the flow stress, σ_f. Then, the maximum value of the coefficient is given by a ratio of the shear yield stress, τ_y, to the flow stress σ_f Hence, using the Von Mises criterion, $\mu = \tau_f/\sigma_f = 1.1552/2$, where $\mu_{max} = 0.57$ or $m = 1$.

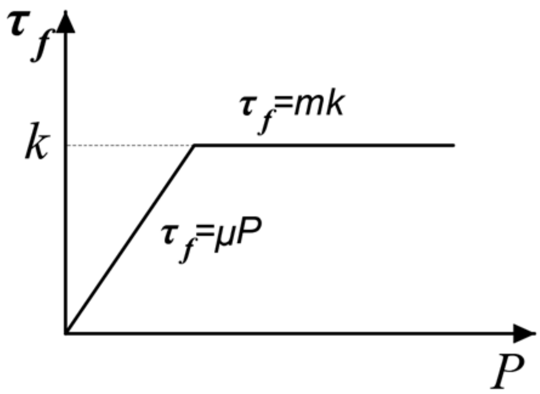


Figure 9 Relationship between contact pressure and frictional shear stress

Several studies have expanded the approach of approximating the friction equations to achieve a better estimate of the material flow [38][48]. According to Tan [48], the method known as a general friction law, gives a better solution in the analysis of finite elements. The frictional stress, τ is described by;

$$\tau = fa\tau_f \tag{6}$$

Where f is the frictional factor, a is the ratio between the real and apparent contact areas and, τ_f is defined by $\tau_f = \sigma_y/\sqrt{3}$.

The above approximation in the estimation of p is graded under the theorem of limits of plasticity theory or more specifically known as the lower and the upper bound theorem [49]. This approach is valid for a steady state problem. There is difference assumption under different approach (see Table 1):

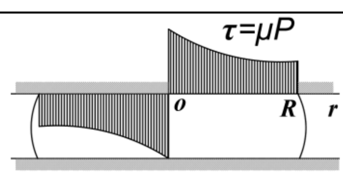
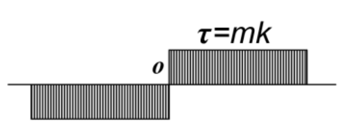
Based on experimental findings, multiple studies were performed to model the friction stress as a function of the distance from the deformation zone. The main difference between these theories as shown in Table 1 is the assumption of the type of friction (viscous or sticking and slipping) and how the tool/workpiece interface distributes the frictional stress. In particular, these techniques are hardly used by current FEM codes, but attach a friction model generally to the whole tool/workpiece interface interaction zone and for the entire process (Table 2).

Many researchers have conducted the metal forming test and used the Trecca shear friction model as shown in Table 2, such as the work done by Harikrishna *et al*. [58], who investigated the FEM Simulation Analysis of Ring Compression Test Using Stationary and Rotating Die under Constant Shear Friction using a stationary and rotating die (TSF). It seems that the usage of Tresca shear friction has a high connection to experimental results, and the findings also show a resemblance to the findings of Yahaya *et al* [59].

Another model of friction is Coulomb shear friction (CFC) is one of the most well-known friction models that has been utilised in metal forming processes, according to a research by Sofuoglu and Rasty [60], who investigated the measurement of friction coefficient using the ring compression test to determine the friction coefficient and in the end, it was discovered that the usage of coulomb shear friction as a simulation model for the research study has good interpretation, and that the experimental model can be approximated simply using the simulation. This study investigation has the same results as Robinson *et al.*, [61], who used the CFC model to arrive at their conclusion, and the outcome is comparable.

There have also been a few researchers who have advocated for the employment of both friction models, i.e. the Tresca shear friction and the Coulomb shear friction as explored by Zhang *et al*., [62], to study the connection between these two friction properties. The findings showed that the ratio (k) of Coulomb friction coefficient to Tresca friction factor changes depending on whether the friction is lubricated or not (dry). Under lubricated circumstances, the ratio k may be characterized by a parabolic function, whereas under dry conditions, it can be described by an exponential function.

Table 1 Friction models in bulk metal forming [50]

Friction model	Friction stress distributions	Main assumptions and applications	Reference
$\tau = \mu P$		➢ Dry slipping occurs over the whole tool/workpiece interface ➢ Friction stress τ is directly proportional to local normal pressure p ➢ It is mainly used for cold metal forming due to its simplicity.	Von Karman, [51]; Kunogi, [52]; Kudo, [53];
$\tau = m\tau_f$		➢ Dry slipping occurs over the whole tool/workpiece interface ➢ $\tau_f = \sigma_y/\sqrt{3}$ is the shear flow stress, and σ is the yield stress. ➢ Since its simplicity, it is the most popular model and seems to suggest the material feature of plastic deformation.	Siebel, [54]

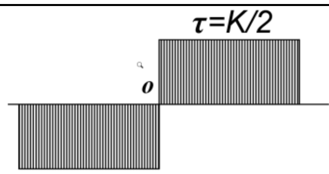
Friction model	Friction stress distributions	Main assumptions and applications	Reference
$\tau = \frac{K}{2}$		➢ Sticking occurs over the whole interface between tools and workpiece ➢ $k = 1.15\sigma_0$. ➢ It is used for hot metal forming or unlubricated cold forming of "soft" materials.	Orowan, [47]; Sims, [55]; Alexander, [56]

Table 2 Friction models normally applied in FEM

	General expression	Near the neutral point	Reference
Coulomb friction model	$\tau = \mu P$	$\tau_n = \mu P \left\{ \frac{2}{\pi} arctan \left(\frac{\lvert u_r \rvert}{u_0} \right) \right\} \frac{u_r}{\lvert u_r \rvert}$	Chodnikiewicz *et al.*, [57]
Constant friction model	$\tau = m\tau_f$	$\tau_n = m\tau_f \left\{ \frac{2}{\pi} arctan \left(\frac{\lvert u_r \rvert}{u_0} \right) \right\} \frac{u_r}{\lvert u_r \rvert}$	Kocaker, [50]

There have also been a few researchers who have advocated for the employment of both friction models, i.e. the Tresca shear friction and the Coulomb shear friction as explored by Zhang *et al*., [62], to study the connection between these two friction properties. The findings showed that the ratio (*k*) of Coulomb friction coefficient to Tresca friction factor changes depending on whether the friction is lubricated or not (dry). Under lubricated circumstances, the ratio k may be characterized by a parabolic function, whereas under dry conditions, it can be described by an exponential function.

2.2.2 Lubrication in Metal Forming Process

Friction, lubrication, and wear between moving surfaces are the focus of tribology. The significance of tribological factors in the formation of bulk metal was generally recognized as influencing the life of the tool, the product flow during the forming, the load applied, the lubricant relationship to the process elements and the surface finish consistency. There are a few different lubricants available for use in metal-forming processes. Water-based lubricants, synthetic oils, and low-viscosity mineral oils are all viable choices for low press-working. Phosphate and other additive and low-friction coatings are often employed in elevated forming processes [63]. The effectiveness of lubricants in forging and other metal forming operations has been investigated by several prior researchers [64-66]. These scientists have not only studied the effects of different lubricants on the deformation process, but they have also monitored other factors such as specimen configuration, coefficient of friction, change in material characteristics, and normal and shear stress. There are three type of metal contact during lubrication in process, that is Hydrodynamic, Mixed and Boundary regimes of lubrication as shown in Figure 10.

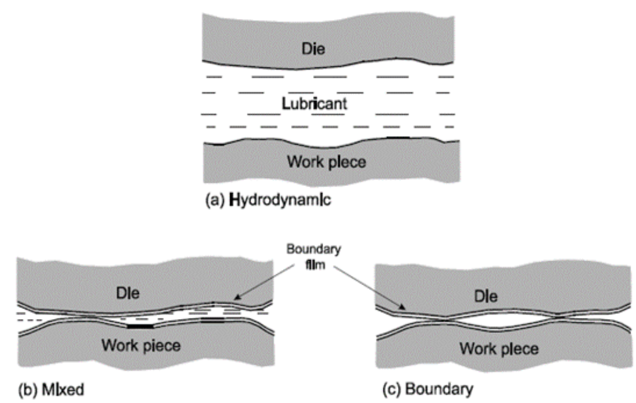


Figure 10 Regimes of lubrication [28]

There have been many iterations of lubricants created and tested for use in the manufacturing sector. Mineral oil, oleic acid, and stearate soap are some of the most often used lubricants [67-69]. Researchers employed a broad variety of lubricants, each of which created a unique lubricated interface state and, hence, a unique coefficient of friction. To this end, researchers have been working on improving lubricant technology and creating novel lubricant formulas. In order to make the normal lubricants suitable for use in a metal working process, chemical additives were added to either lower or replace the quantities of active components. In 2001, Rao *et al*. [70] showed that boric acid worked well as a lubricant for aluminum sheets. Value is equivalent throughout a broad range of forming parameters when compared to other commonly used lubricants such as polytetrafluoroethylene (PTFE), molybdenum disulfide (MoS_2), graphite (Graphite), and oleic acid.

It was recognized that the efficacy of lubricants used in metal forming depends on many variables such as thickness of lubricant, viscosity, original contact surface, magnitude of the load, chemical reaction between contact surface and movement speed [71-73]. Lubrication is the process of providing the wearing interface with either air, liquid or solid powder that serves as a film medium or promotes chemical transformation into a film material. Different types of lubrication regimes can be related to a mechanism that can be considered the most significant lubrication element in metal formation. Lubrication is controlled by different physical and chemical factors in each regime. As a result of minor changes in lubricant and workpiece materials, various regimes may occur, such as speed temperature, speed, surface roughness and geometry. Figure 8 described and highlighted the three major regimes concerned.

There are four primary lubrication mechanisms (i.e. dry / boundary /mixed film / hydrodynamic) observed in metal forming processes. As shown in Figure 11, the Stribeck curve illustrates the onset of these various types of lubrication as a function of lubricant viscosity, *η*, sliding velocity, *v*, and normal pressure, *p* [75].

In a dry state, there is no lubrication between the two surfaces, hence friction is increased. This is an ideal state to achieve just in a few forming processes (e.g. hot rolling of plates or slabs and non-lubricated extrusion of aluminum alloys). When two solid surfaces are in such close proximity to one another, surface interaction between mono- or multi-molecular layers-of lubricants and the solid asperities becomes the dominant contact mechanism [76].

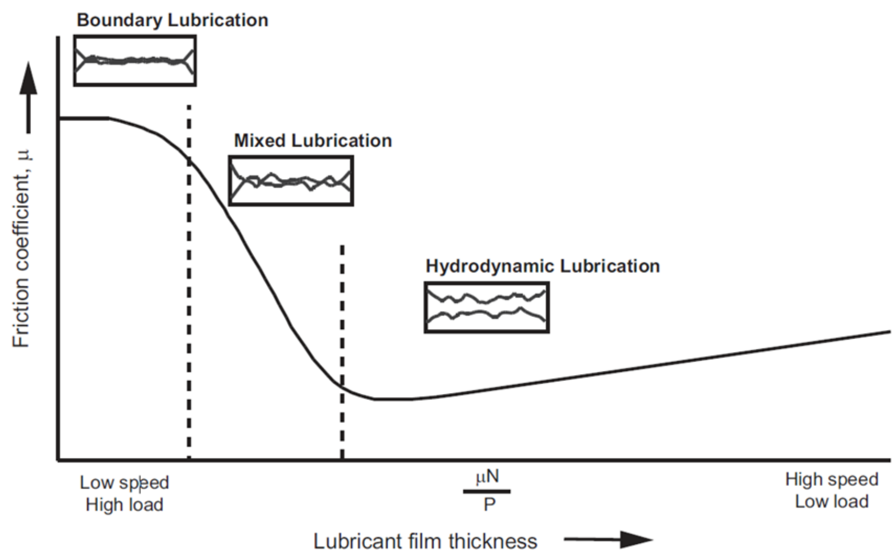


Figure 11 Stribeck curve graph [74]

For most stamping, forging, and hydroforming operations, boundary lubrication is the most common lubrication state. It is also common for sheet metal forming to involve mixed-layer lubrication. In this case, the micro-peaks of the metal surface experience boundary lubrication conditions and the micro-valleys of the metal surface become filled with the lubricant. In metal forming, hydrodynamic lubrication is a rare occurrence that only happens under extremely particular temperature and velocity circumstances (e.g. sheet rolling operation).

The Stribeck Curve is a friction plot as it relates to speed, load and viscosity. The friction coefficient is on the vertical axis, *f*. The horizontal axis presents a function combining the other variables, $\mu N/P$, where N is the relative speed, μ is the viscosity and P is the force on the contact [77]. Stribeck curve is literally related to the concept of tribology, where the science and technology of interacting surfaces in relative motion is concerned. This includes understanding and applying the concepts of lubrication, wear and friction.

Numerous research has examined the impact of lubricant viscosity in metal forming processes so far. Higher viscosity mineral oil was investigated by Kawai *et al*., [78] under lubricated and dry frictional circumstances. In the dry frictional condition, the metal surface was polished smooth, in contrast to the lubricated state, when the frictional surface increased by over 26 times. However, no seizures were seen throughout the extruded journey. In their plane strip drawing of modified aluminium sheets, Bech and Eriksen, [79] found that higher interface gradients (decreasing pressure towards the exit) lead to higher friction when viscosity is lower.

Loads tend to diminish as long as oil remains in the contact, as pointed out by Shirizly and Lenard, [80]. Lee *et al*., [81] used a variety of drawing oils in their analysis to show that when the viscosity of the lubricant decreased, the coefficient of friction increased. Also, surface roughness may go from very smooth to very rough if the coefficient of friction is significant.

For the purpose of cold rolling low carbon steel strips, Dick and Lenard, [82] conducted an experiment utilizing three different commercial oil-in-water emulsions. Unexpectedly, they discovered that oil viscosity had minimal to no impact on the loads. There may have been less strain with greater roll roughness as a result of the increased speed. Golshokouh *et al*., [83] utilized palm oil with a greater viscosity to test the impact of employing a vegetable oil as a hydraulic fluid on the efficiency of a hydraulic system. An increase in oil viscosity was shown to be responsible for an improvement in volumetric efficiency over the ageing period. In addition, vegetable oil degrades more quickly than mineral oil, leading to a marked rise in viscosity as the oil aged.

A study by Syahrullail *et al*., [84] identified that high viscosity palm oil-based lubricant, RBD palm has a decent opportunity of lowering the friction and extrusion force. It is because the lubricant has the capability of reducing the frictional constraint in the cold metal forming which is similar to the mineral base lubricating oil. However, the existence of RBD palm stearin in a solid state at room temperature affects the surface condition of the work piece as a coarser roughness condition is observed in cold extrusion. Likewise, Norhayati *et al*., [85] discovered that the extrusion load and frictional constraint were reduced even when the experiment was conducted on the redesigned surface of the taper die. Researchers Hafis *et al*., [30] observed that by applying the proper amount of lubricant, the load might be lowered after testing a semi-solid mineral oil. Different oil viscosities were tested on a textured track surface and compared to a smooth track surface in a scientific study by Sudeep *et al*., [86]. According to the results, oil with a greater viscosity may reduce the friction value of the textured track surface.

2.3 Analysis for Metal Forming Process

2.3.1 Nature of Material Flow

Analyzing the properties of a considered trying product or material has always relied on experimental methods. The same can be said regarding the metal forming process, where this approach has been widely adopted by researchers from all around the world. Extrusion load, sliding velocity, force, metal flow pattern, and influence of temperature are the most often analyzed variables in metal forming. The process includes research into the nature of the flow of materials both before and after metal is formed.

In most cases, the size of the metal that was mined was larger than the final product's dimensions required for fabrication. Therefore, metal forming processes like forging, extruding, or rolling are necessary to distort the thick rod and bring it down to the appropriate size. There's no doubt that this procedure devours a lot of resources and necessitates pricy equipment. Therefore, it is essential to understand the optimal forming loads required to produce the necessary substantial deformation.

Several studies up to this point have focused primarily on the study of forming loads in metal forming processes. Researchers Lakshmipathy and Sagar, [87] looked at how the direction of die grinding marks affected friction in lubricated open die forging. Both the work piece and the die were made from commercially pure aluminium and H11 steel. It was discovered that the forging loads and friction might be reduced by using a crisscross grinding pattern between two sets of die instead of a single, straight grinding route.

Kim and Kim, [88] performed friction and wear studies to learn how sliding velocity and normal load impact the tribological properties of a diamond-like carbon (DLC) coating for machine components. Sliding velocities ranged from 0.0625 m/s to 2 m/s, with normal loads ranging from 6.1 kN to 49 kN, and temperatures were kept constant during all experiments against AISI 52100 steel balls. A higher sliding velocity and normal load both lead to lower friction coefficients. A higher sliding velocity also causes wear rates to rise, eventually reaching a maximum.

Figure 12 shows the schematic of the four different types of flow in extrusion process. When friction is not present between the container and the die contacts, the flow pattern S is called an extrusion of homogenous materials. Flow pattern C, which results in a non-uniform temperature distribution in the billet, was chosen to accommodate the billet's heterogeneous material qualities. Closer to the wall of the container, materials experience more shear deformation and develop a larger dead-metal zone. The existence of friction in homogenous materials during the extrusion process results in flow patterns A and B. Unlike flow pattern A, in which friction is just at the die surface, flow pattern B has friction at both the container and die interfaces. As a result, Flow Pattern A works well for Indirect Extrusion, whereas Flow Pattern B is dependable for Direct Extrusion. Because a longer dead-metal zone develops on flow pattern B, shear deformation also increases there.

2.3.2 Surface Finish and Precision

Tests for surface finish and precision are required to investigate product quality. All stages of material extraction and manufacturing are vulnerable to the effects of friction and wear [90]. Several factors must be taken into account in order to lessen the friction, wear, and surface roughness. Numerous research up to this point have revealed factors that have been linked to such issues. Geiger *et al*., [91] state that characterizing and qualifying the surface of the work piece during metal forming depends on a firm grasp of the trapping behavior of liquid lubricant and the contact behavior of asperities at the tool work piece interface. Therefore, a proper lubricant choice may aid in mitigating the significant impact of such defects. Figure 13 shows the sample analysis for surface finish that been done by Aiman *et al*., [3], [6] that study the effect of surface workpiece that lubricated with different derivatives of palm oil.

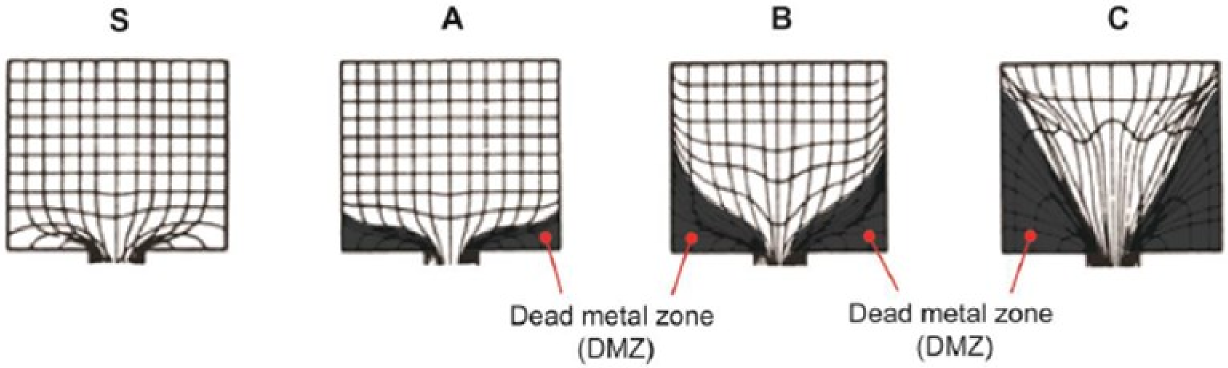


Figure 12 Schematic of the four different types of flow in extrusion, S: frictionless; A: friction at die surface; B: friction at both container and die surfaces and C: more friction at container wall with more extended dead metal zone [89]

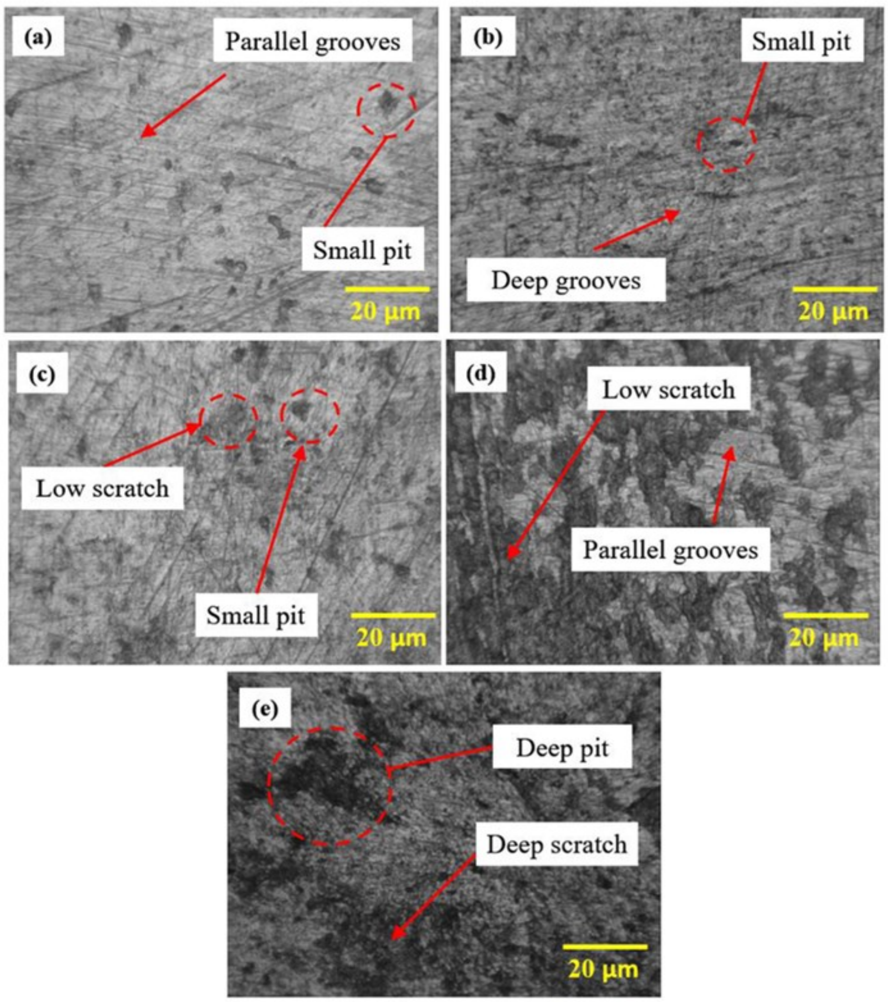


Figure 13 Optical Micrograph under 10X Image at full deformation of workpiece for (a) Na–O, (b) PMO, (c) PKO, (d) CMFO and (e) PS at 50% deformation [3], [6]

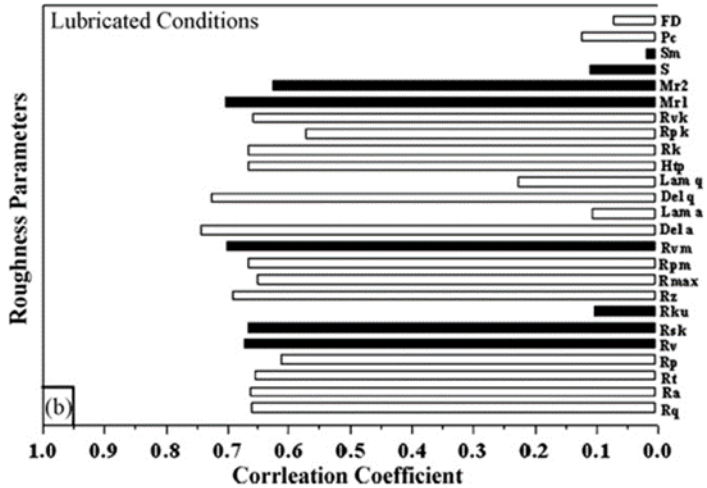


Figure 14 Correlation coefficient between coefficient of friction and roughness parameters under lubricated conditions. [92]

Surface roughness of the die is a crucial component influencing friction, which plays a vital role in metal forming operations as proposed by Menezes *et al*., [92]. Figure 14 shows the analysis of typical roughness parameters that reflect to the correlation coefficient in order to analyze the surface of the metal. Friction has a significant impact on the contact area between die surfaces and drawing direction, as determined by Costa and Hutchings's, [93] research that set out to quantify these effects. Another method of surface analysis is based on surface topography as shown in Figure 15 which provide more detail on how surface behavior after the deformation process.

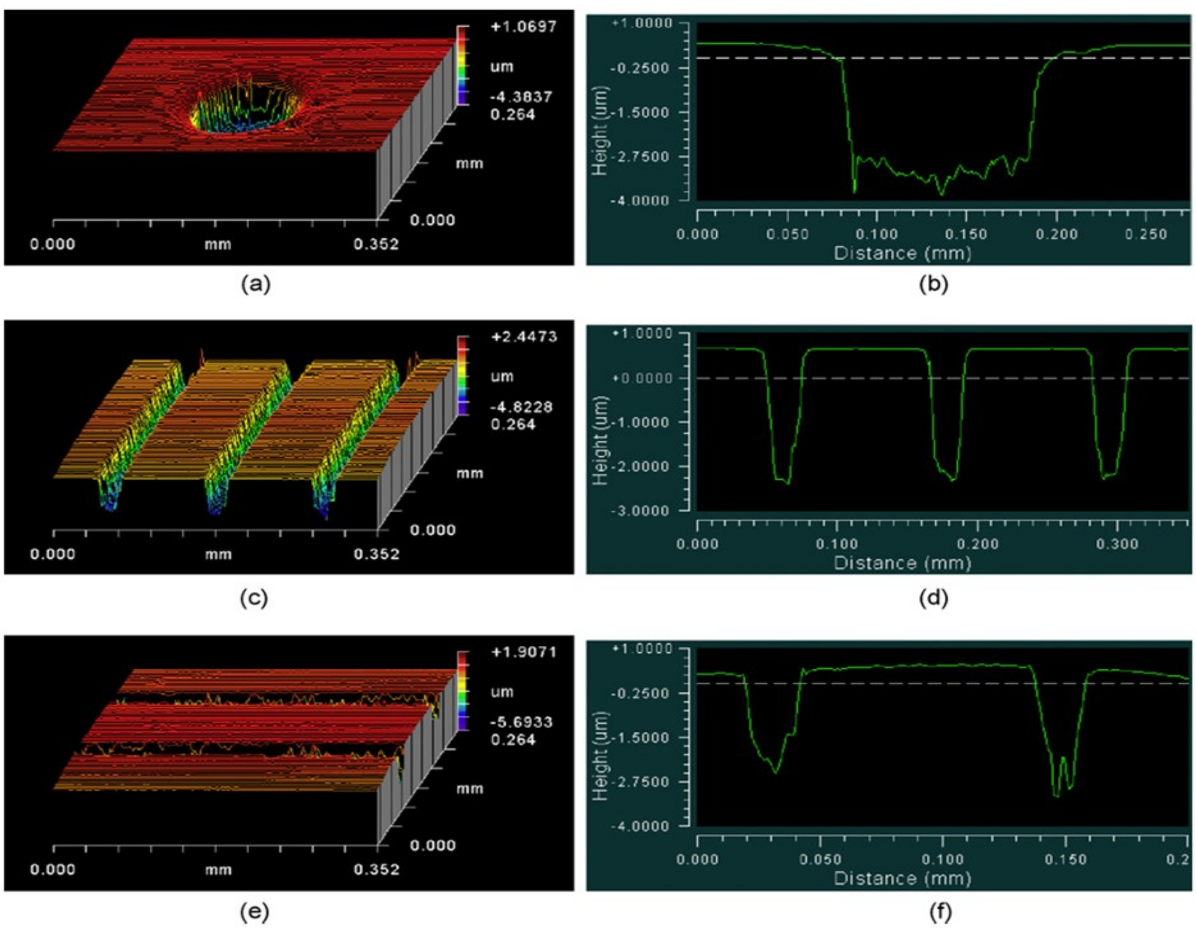


Figure 15 surface topography of the textured die surfaces: left, perspective views; right, line profiles. (a) and (b) Sample ST1; (c) and (d) sample ST2; (e) and (f) sample ST3. All data were generated by optical profilometry. [93]

Since cold forming was selected as the metal forming procedure for this investigation, it was crucial to look into how these factors affected the forming process itself. The longer the billet is, the more friction it will encounter as it advances through the taper die, leading to a greater compression force [94]. While some friction is required for metal forming operations, too much may cause die wear, which in turn can disrupt metal flow and lead to product flaws [95-96]. Many researchers are devoting time and energy to finding solutions to the problems of friction and wear in materials processing because they are so important to the efficient and safe extraction and primary processing of raw materials.

3.0 MATERIALS AND LUBRICANTS SAMPLE TEST

Testing the viscosity and density of a lubricant is crucial for categorizing each lubricant according to its unique qualities. A fluid's viscosity is linked to its density, with a greater density potentially resulting in a more viscous fluid. The temperature of the fluid also plays a role in its viscosity; a decrease in viscosity may occur at higher temperatures. On the other hand, gas behaves differently, with its temperature tending to rise.

A variety of tests, including tensile tests, hardness tests, and heat treatments, are often performed on experimental materials before they are put through the rigors of the actual experiment. It is useful for amplifying findings from other testing parameters; thus, it should be employed for that purpose. In order to determine whether or not a material can resist a certain stress level before breaking, a tensile test must be performed. The ductility of a material may be evaluated by calculating its elongation at break and flexural strength under tensile stress. In contrast, since there is no material provided on this feature, the material is at risk of fracturing or rupture when it is exposed to overload loads. Metals must have certain characteristics, and hardness is one of them before they can be formed. In order to choose the appropriate material for tooling and work piece, hardness testing, a destructive method, plays a key role. A tooling part's substance, in order to deform a work piece into the correct shape, must be harder than the work piece. Offering compliant items that are to the satisfaction of the final consumer might help lessen the likelihood of product failure.

Several researchers have used the same tool hardness value in their analysis. The hardness of dies used in metal-forming operations is summarized in Table 3. Softer work piece materials including pure aluminum and aluminum alloy were employed and tested with a variety of tool steels. From the data in the table, it is clear that the normal range of tooling hardness for metal forming operations, and the cold extrusion process in particular, is between 48 and 66 HRC. Furthermore, because to the high levels of pressure and wear that dies are exposed to, it is necessary for these materials to provide adequate protection against wear, high fatigue strength, and high compression strength [97].

The qualities of the created metals may differ from one another, depending on their intended use. Steel beams used for supporting loads, for instance, are very sturdy. The steel used to make the wall frame must have some ductility so that it can be bent into the right shape without breaking, but it must also be sufficiently strong to prevent cracking under stress. Based on the findings of the prior research, many methods of employing lubricant, testing methodology, and friction analysis were examined in the metal forming process. Mineral oil and molybdenum disulfide were the two types of lubricant samples that were used most often in metal forming. However, some researchers have begun looking into the possibility of utilizing biodegradable oil in substitute of commercial metal forming oil. This is because commercial metal forming oil is made from mineral oil, which is harmful to the environment. Additionally, palm oil demonstrates an intriguing lubricant as a metal forming lubricant, in which part of the fractionated product is obtained only through the use of experimental methods.

3.1 Method Approach and the Used of Bio-based Lubricant in Metal Forming Process and Analysis

3.1.1 Method Approach and Analysis

The open forging test, the extrusion test, and the closed forging test are the typical types of testing that are performed throughout the metal-forming process. These tests are well-known in the scientific community [105]. The most of the test methods involved the use of lubricant throughout the trial. Experimentation is the major technique used in some of the method approaches; however, finite element modelling (FEM) software is now widely used and is a well-known tool that researchers may use to assist them in analyzing the metal-forming process. The most of the lubricated samples used an analysis that focused on the interaction of frictional behavior, and the most of friction correlations are only based on a single form of frictional interaction. The investigation of various kinds of friction that occur during the metal-forming process assists researchers in the process of modelling the most optimal model and assists researchers in observing how various kinds of friction affect the examination of lubricated samples. Table 4 summarizes the methodology and analysis used in previous studies.

Table 3 Summary of tooling hardness for metal forming processes' die

Die material	Workpiece material	Metal forming process	Hardness (HRC)	Reference
Tool steel	Pure aluminum Al99.7	Open-die forging	48	Misirli, [98]
Rigor Caldiea 0741 Sleipner Carbide steel Sverker 21 Vanadis 4E Vancron 40	unknown (Tested for friction measurement analysis)	Sheet metal forming	61 59–60 56–57 61 59 60–61 61–62 61	Kirkhorn *et al.*, [99]
Tool steel 1 Tool steel 2	Aluminum alloy sheet	Impact extrusion	62 66	Schubert *et al.*, [100]
AISI H13 hot work tool steel	AA6063 aluminum alloy	Back extrusion	49.7	Haghdadi *et al.*, [101]
SKD11 tool steel	A1050 pure aluminum	Cold extrusion	58.5	Kamitani, *et al.*, [102]
SKD11 + coating AlCrSiN	unknown (Tested for coating performance)	Cold press	60	Abusuilik, [103]
H13 hot worked tool steel	AZ91 seamless tubes	Radial-forward extrusion	55	Jamali *et al.*, [104]

Ring compression test is one of the famous metals forming test and it is based on open forging condition [4], [23], [106], [68]. Figure 16 shows the typical experimental testing of ring compression test as proposed by Zhang *et al*. [4], [23], where the analysis is based on the deformation of the ring diameter. Extrusion is another method for producing metal that has been suggested by some researchers. Some of the types of approach extrusion processes are the double cup extrusion process, which Lee *et al*. [105] explored, and the cold forward extrusion process, which Nurul *et al*. [23] investigated. Figure 17 represent the typical extrusion experimental set up for both method approach.

Since the sample can be evaluated based on the model sample needed, the closed forging process is one of the flexible metal forming processes with a very wide approach. Figure 18 displays some findings by Aiman *et al*. [3][6] study that used a closed forging process, where the process involving a mold for the workpiece.

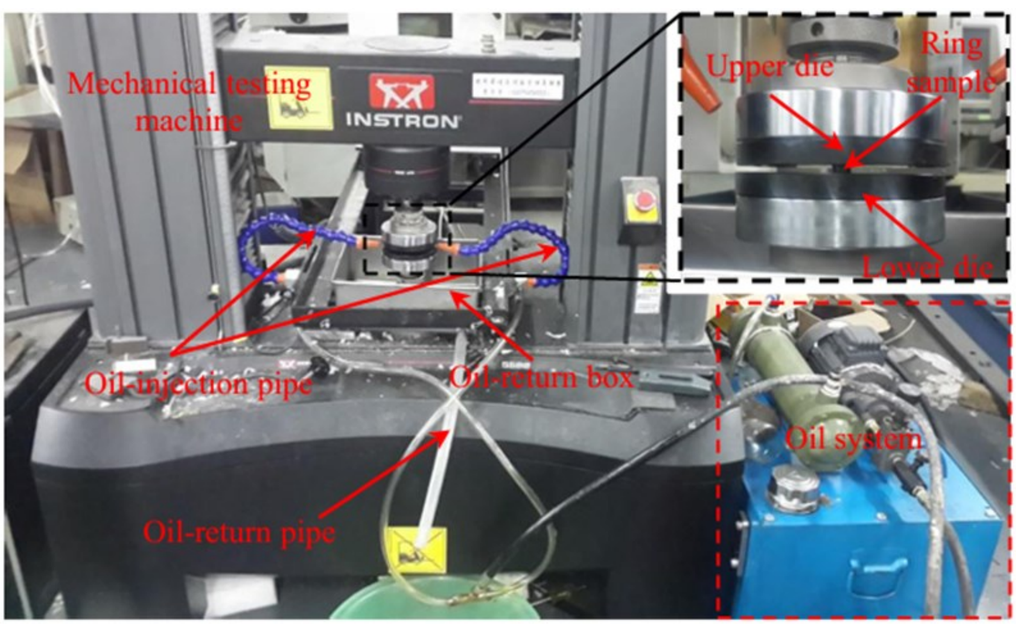
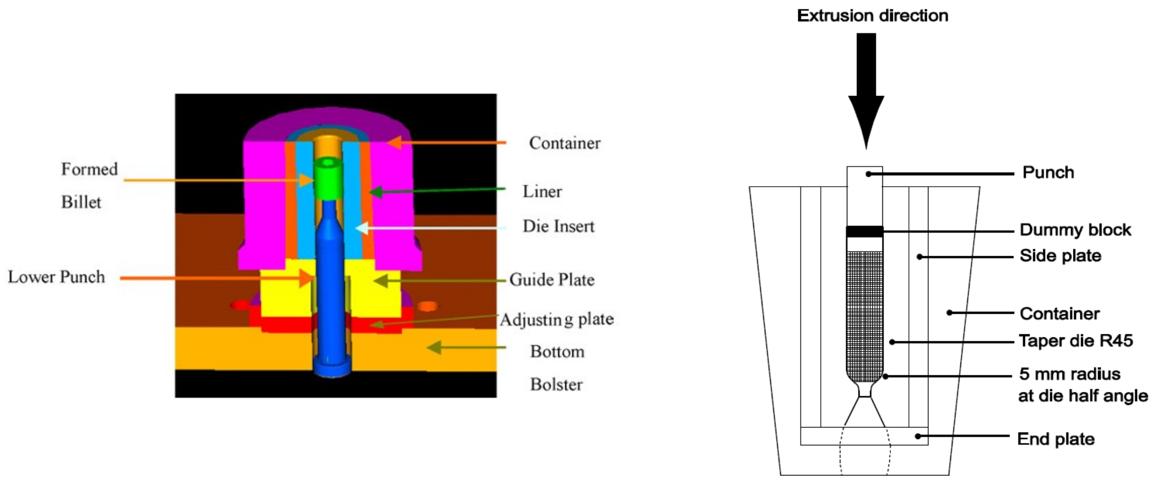


Figure 16 Installation of ring compression test as proposed by Zhang *et al*. [4], [23]



(a) (b)

Figure 17 Type of experiment set up for extrusion process (a) Double cup extrusion process and [105][110] (b) Cold forward extrusion process [30], [113], [114]

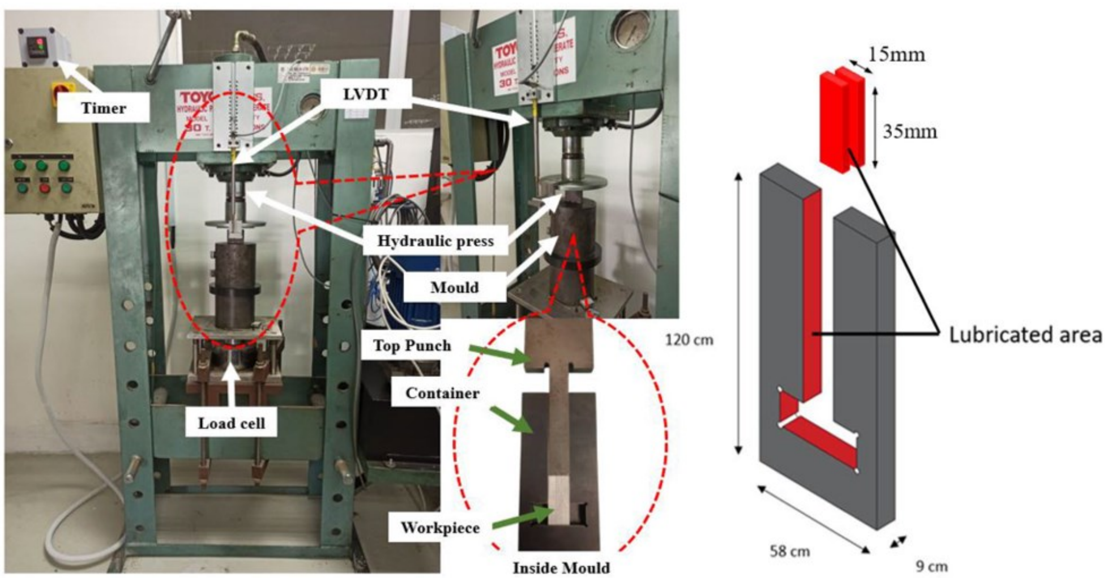


Figure 18 Experiment setup and sample arrangement of closed die forging [3], [6]

Table 4 Reports on lubricant and analysis for metal forming processes' die

Metal forming test	Workpiece material	Lubricant sample	Testing approach	Friction analysis	Reference
Ring compression test (open forging test)	#45 steel (American grade 1045) AISI 1045	-	Experimental and FEM	Coulomb and Tresca friction	Zhang *et al.*, [4][23]
	AA5052	M_oS_2	Experimental and FEM	Coulomb and Tresca friction	Zhang *et al.*, [106]
	Mild steel	Mineral oil (VG2, VG15, VG 100) and beef fat	Experimental and FEM	Coulomb friction	Tatematsu *et al.*, [107]
	Pure Aluminum AA1100	Ground nut oil, palm kernel oil, black soap, sheabutter oil, red palm oil	Experimental	-	Abdulquadir and Adeyemi, [108]

Metal forming test	Workpiece material	Lubricant sample	Testing approach	Friction analysis	Reference
	AA6061	CM202A, Zinc phosphate, rapeseed oil and soybean oil	Experimental and FEM	Coulomb and Tresca friction	Zareh and Davoodi. [68]
	AA6082	Grease and mineral oil	Experimental and FEM	Coulomb friction	Priyadarshini *et al.*, [109]
Extrusion test	AA6082	Soap M_oS_2	Experimental and FEM	Tresca friction	Schrader *et al.*, [110]
	AA2024	Mineral oil	Experimental	-	Lee *et al.*, [105]
	A1100	Palm stearin, VG95 and 460	Experimental	-	Syahrullail *et al.*, [111-112]
	Pure aluminum	Palm stearin, palm kernel oil, daphne, VG95 and 460	Experimental	-	Nurul and Syahrullail, S. [113-114].
	16MnCr5 Hardening steel	M_oS_2, wax and polymer	Experimental and FEM	Tresca friction	Lorenz *et al.*, [115]
Closed forging test	Magnesium alloy	-	Experimental and FEM	Tresca friction	He *et al.*, [116]
	AISI 1010	Phosphate, Sinol draw 891 and mixed of both	Experimental and FEM	Tresca friction	Zhang *et al.*, [4]
	Al 6061 Al 2024	VG32, VG100 and Grease	Experimental and FEM	Tresca friction	Jung *et al.*, [117]
	A6061-T6	Coating of solid lubricant	Experimental and FEM	Tresca friction	Sagisaka *et al.*, [118]
	Al 2024-O Al 6061-O Al 7075-O	Grease, corn oil, and VG32/100	Experimental and FEM	Tresca friction	Jung *et al.*, [119]
	CrMoV alloy steel	VG32, grease and dry PTFE lubricant	Experimental and FEM	Tresca friction	Hu *et al.*, [120]
	AA 1100	NA-O, CMFO, PKO, PS, and PMO	Experimental and FEM	Tresca friction	Aiman *et al.*, [3][6]
	AISI 1010	-	Experimental and FEM	Tresca friction	Al-Shammari *et al.*, [121]

3.1.2 Lubrication Sample Derived from Bio-based Lubricant

A few researchers have tried to design a more sustain lubricant that may be utilised to replace the mineral oil-based lubricant. Tatematsu and his colleague [107] investigated the usage of beef fat in comparison to mineral oil-based lubricants in 2018, and the results suggest that beef fat has reduced friction in ring compression tests, where the deformation of the workpiece has the maximum formation. However, the result was limited to the friction and distribution of stress in workpiece only, the information on the surface behaviour of the workpiece is not discussed clearly.

When discussing lubricants made from renewable resources, vegetable oil is often cited as one of the most significant sources currently available. In the process of metal forming, Abdulquadir and Adeyemi [108] have discussed how crucial it is to employ lubricants made from bio-based materials. In their research, a few vegetables oil (palm kernel, groundnut, shear butter and red palm oil) has been selected as metal forming lubricant and been compared to the black soap sample as a benchmark lubricant. From the result it shows that some vegetable oil sample has a lower friction compare to black soap, that is red palm oil and sheabutter oil. The lower friction for both of the sample oil is may due to the different contamination of free fatty acid composition inside the lubricant as discussed by Aiman *et al.*, [33], where he addressed that the higher in unsaturated fatty acid in the lubricant has a stronger bond to break during the metal-to-metal contact that can reduce the friction. Campen *et al.*, [122] confirmed that this double bond caused the oleic acid (unsaturated) to form cis-configuration which bend the molecules and hard to adopt linear molecules configuration. Unsaturated fatty acids are therefore far less efficient in forming tightly packed monolayer soap films. Less compact packing density causes fatty acid chain molecules to have less attraction for metal surfaces. Meanwhile, the molecules of palmitic and stearic acid, which are saturated fatty acids, have a great capacity to pack tightly and effectively on metal surfaces [123-124].

Another research that using vegetable oil based in metal forming is done by Syahrullail *et al.*, [111-112], [125] that using palm stearin as metal forming lubricant and later be developed by Nurul in [113-114] that use another type of palm oil based with modification of mould die in getting the most appropriate mould design in reducing the compression force and improving the extrusion process. From their research, palm oil based has potential to be utilize as metal forming lubricant, where the friction coefficient of palm oil based is somewhat lower compare to the mineral oil based [112]. This finding has been proved by Nurul in 2015 and 2016 where it shows that palm stearin has better performance compare to VG 460 and VG 95 (viscosity grade mineral oil) [113-114]. At room temperature, RBD palm stearin exists in a semi-solid state, and it completely transforms into a liquid at 40°C. It's important to note that PMO VG460 is thicker than PMO VG95 and may move more slowly during the extrusion process. The extrusion process will be easier and require less force thanks to this physical condition. The modification of the taper die during research shows an improvement in extrusion process where the extrusion load has decrease significantly for the taper die with the micro pit [126] for both type of lubricant (vegetable and mineral oil based).

4.0 CONCLUSION

This article provides a thorough analysis of current advancements in the field of metal forming, including, tribological in metal forming, method approach of metal forming testing, and the use of bio lubricants as metal forming lubricants. According to this assessment, the metal forming process involves a variety of testing methods, the majority of which are by experimental testing. To improve the scientific study, a finite element analysis is required to observe stress-strain within the workpiece under various levels of lubrication and to assess friction during compression. There is still a dearth of theoretical knowledge of the many lubrication processes, despite the fact that some of these mechanisms have been documented in the scientific literature as being responsible for increased tribological performance. In order to have a complete understanding of the lubricating mechanism of the metal forming process, more research studies, both theoretical and experimental, are required.

Most metal-forming lubricants were mineral oil-based, and the introduction of bio lubricants has attracted the attention of scientists as a means of creating a manufacturing process that is more environmentally friendly. From this review, a few researchers have started the used of bio lubricant in their research that's come from animal and plant. According to the findings of the study, several of the bio-lubricants have the potential to be used as metal forming lubricants due to long polar fatty acid chain and molecules are able to provide protection on the contact surface, thus resulted in less wear and friction. Besides that, the present of unsaturated fatty acid also able to reduce the contact impact between the workpiece and the packed alkyl chain, which reacts with the cumulative short range of van der Waals forces that exist between neighbouring groups. A greater amount of closed-packed material led to improved affinity on the metal surface where the unsaturated fatty acid has a double bond on its ninth and tenth carbon chain, which separates it from saturated fatty acids. Nevertheless, most of the technique of testing in bio lubricant were restricted to experimental testing only. In order to conduct in-depth research on vegetable oil, a few different methodologies, such as the finite element technique, are required.

Conflicts of Interest

The author(s) declare(s) that there is no conflict of interest regarding the publication of this paper.

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