A Formulation on Friction in Forging

Submitted by
Margarita Tsarkouskaya

Industrial and Systems Engineering

To
The Honors College
Oakland University

In partial fulfillment of the
requirement to graduate from
The Honors College

Mentor: Dr. Sergey Golovashchenko, Professor of Engineering
Department of Engineering
Oakland University

April 2, 2020

Abstract

Metal forging is frequently used for the manufacturing and production of parts for many industries. While the process has improved with automated equipment, there are still many unknown factors about the causes of friction in forging dies during the process. Friction is important to account for because the quality of the forged parts depends upon the interaction of the metal and the tool during the forging process. This interaction is subject to the negative effects of friction when there is a lack of compatibility between materials, lubricants, and multiple other factors. In particular, the focus of this research will be to study how friction depends on different conditions in metal forming as an industrial process. An evaluation of the forging conditions' impact on the coefficient of friction will allow recommendations to be made on how to further improve the forging process to effectively reduce friction and guide future experiments related to the occurrence of friction.

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Introduction

Among the many processes that exist for shaping metal, forging is one of the most common ones. It is used by a multitude of industries such as aerospace, machinery, transportation, and construction as well as others [1]. Its wide range of application is due to its ability to be used with an extensive number of metal alloys and produce a variety of part sizes [1]. Additionally, the process is cost-effective because it uses nearly all the metal employed and thus, is highly preferable in industry [2]. However, as with any process, it has its limitations. One of the most significant factors that constrains the quality of the finished forged product is friction. While the process has become more refined with automated machining, friction that occurs during forging is a big challenge in the industry because its causes are not well known. This paper will explore the possible causes of friction that occurs during forging, its effects and suggest possible improvements to the process.

Metal Forging Process

Forging consists of the use of compressive forces to shape metal into its desired form. These forces are applied to the workpiece repeatedly, which is also known as cyclical loading. The application of the force depends on the type of metal forming process being used, with the means used to apply the force called dies. There are four main categories that forging methods can be classified by: open die, impression (or closed) die, ring rolling, and extrusion [3]. These are exhibited in Figure 2.

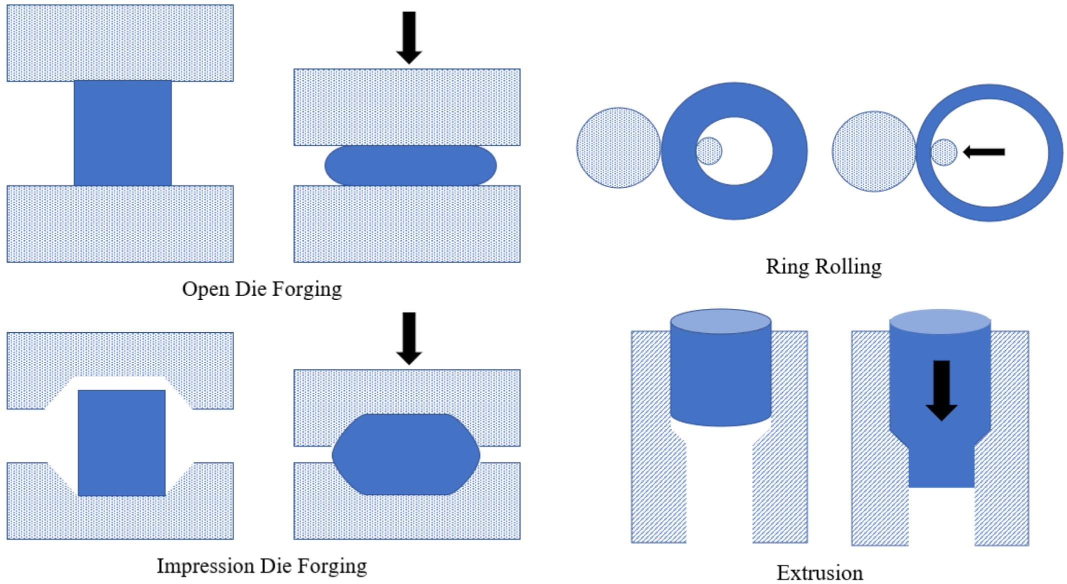

Figure 1. Types of forging processes

Open die forging is typically unconstrained, in terms of metal flow. This type of forging is used to produce large batches of parts, with the manufacturable quantity often exceeding that of impression die forging. Impression, or closed die, forging limits the movement of the metal to the shapes contoured within the dies themselves. This process gives parts better dimensional precision than open die forging because the metal workpiece is constrained. Ring rolling involves two rolls, with one moving inwards towards the other, increasing the diameter of the workpiece while decreasing its thickness at the same time. During extrusion, metal is pushed against the walls of the dies and elongated or thickened.

Temperature also plays a role in the process. Hot forging involves heating up the workpiece and is most often used with open die, impression die, and ring rolling processes. Cold forging is performed at room temperature with many of the processes being a form of extrusion. Warm forging is a modification of cold forging where the workpiece is heated just enough to make the metal workpiece more malleable.

For conciseness, this paper will focus on cold forging. Cold forging is called as such because it requires no heating and is performed at room temperature. This results in greater dimensional accuracy of the produced part and high efficiency in the production of large quantities [3, 4]. On the other hand, the reduced temperature results in lower plastic flow of the material which necessitates higher applied forces to be used, in contrast to other types of forging. In turn, both these factors cause greater friction to occur between the metal part and the forging dies.

Friction in Forging

Friction is the resistance to motion that is created between two contacting objects, demonstrated as occurring at the dotted line in the figure below. Such resistance is prevalent between the metal part being forged and the forging die used to apply force. The coefficient of friction can range anywhere from 0.02 to 0.1 [5, 6]. This evaluation depends on the means of testing, type of friction model used, and the level of abstraction in assumptions. The higher the coefficient, the greater the negative impact on the forged part and the forging tool.

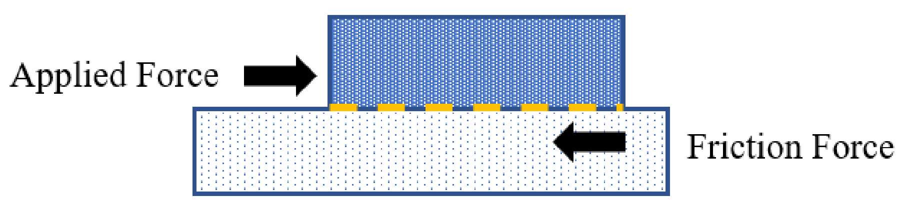

Figure 2. Creation of friction

The exact causes of friction during forging are not well known. It is assumed to result from a combination of multiple factors consequently making friction difficult to estimate and control [5, 7]. Adding to the complexity is the dynamic variation of friction during the multistage forging operations [6, 8, 9]. So, while at least a dozen of friction tests and models exist, at present it is extremely challenging to accurately evaluate friction in forging. However, by using the premise of these tests and analyzing their considerations, hypotheses can be drawn about which conditions have the greatest probability of increasing friction during forging.

Impact of Friction on Forging Processes

Regulating the friction present in forging is important because of the negative effects' friction has on the quality of forged parts as well as the lifetime of the forging dies. Since metal experiences high flow stresses at room temperature, cold forging requires high tribological loads that create considerable demand on the die [2, 4, 8]. As the forging die ages with cyclical loading, the surface of the die that contacts the metal begins to roughen due to fatigue and wear from the high contact stress [10]. Typically, this results in the increase of friction and strain during the process itself, often leading to the initiation of cracks in the tool and in the forged product, as well as increased energy consumption. Increased friction also simultaneously accelerates the deterioration of the forging die [10, 11]. Other impacts include complications with metal flow inside the die, unequal strain distribution, and increase in the forming load applied overall limiting the efficiency of die performance [4, 5, 8]. Therefore, the understanding of friction that occurs during forging aims to prolong the lifetime of forging tools, which would decrease manufacturing costs, as well as maintain the high quality of forged products that manufacturers seek. Being able to calculate an accurate coefficient of friction would help ensure friction remains low during the forging process by allowing changes in the coefficient to be monitored throughout the lifetime of the tools. Simulation is increasingly relied on for the progression of technology development, but detailed simulations require realistic models. This can only be possible by understanding the conditions that pertain to the creation of friction in the forging process.

Forging Conditions Affecting Friction

As previously mentioned, numerous factors affect the prevalence of friction in forging making it difficult to determine which of the process variables has the greatest influence on friction. The words “conditions” and “variables” will be used interchangeably throughout this paper because each forging condition is a variable of the forging process itself. This is reflected in attempts to model friction occurrence with the industry conflicting between using constant and variable friction models for greater accuracy in calculating the coefficient of friction [5, 7, 9, 12]. The models themselves depend on assumptions about which conditions cause or have the most effect on friction. In forging friction studies and experiments, the following conditions are most considered: lubrication, forging pressure, surface topography, part geometry, deformation velocity, tool-workpiece interface temperature, and material properties. A brief discussion of each condition follows.

Lubrication

Lubrication is one of the most studied variables of the forging process. By design, lubricants are meant to reduce the friction stresses and wear that forging dies and workpieces experience by encouraging the deformation of the workpiece [10]. A good lubricant satisfies two parameters: promotes a low friction coefficient and possesses high sticking strength to the metal to prevent galling, or the dragging of material when contact under extreme pressure occurs [13]. Efficient lubricants can thereby improve product quality and tool life while poor lubrication can instead increase the forming load and reduce shape precision [4, 10, 14]. When compared to lubricated tools, use of clean tools has shown a 30% increase in friction values [2]. When no lubricant is used, the process results in high forming load, high contact pressure, uneven surface finish, and non-uniform part geometry as a result of the high friction that occurs [4, 14]. In fact, remaining lubricant on the tool has been shown to significantly influence and decrease the coefficient of friction too [2, 6]. Pre-lubrication of the tool is also an alternative for decreasing friction. This prevents thinning of the lubricant film during forging and has shown that, even when used with unlubricated workpieces, minimal adhesion is detected and the friction coefficient can be lower than when using only lubricated workpieces [2].

Lubricants are applied as a gas, liquid, or solid residue which function as a film material between interacting surfaces [12]. These coatings need to have sufficient strength to withstand the sliding, rolling or other impacting contact that occurs during the forging process in order to effectively reduce friction and wear. Due to the extreme force with which contact between the workpiece and forging die occurs, the surface layers of lubrication films can be swept away during the process [2]. When the intervening lubricant films are removed, the strong adhesive bonds that form between the contacting surfaces cause high friction values to occur. This leads to the tool and workpiece tearing fragments from each other's surfaces, causing wear on the die and decreasing the quality of the forged product. Therefore, it is crucial to understand what amount and type of lubrication is able to provide protection for the contacting surfaces against the forces of the forging process [2, 5, 14, 15, 16].

The amount often depends on the type of lubricant used – liquid, solid, and the chemical composition. Film thickness is important to determine for each kind of lubricant, because if there is too much of a lubricant, the metal will be more difficult to deform. On the other hand, if there is too little, the lubricant won't be able protect against the friction forces. Liquid lubricants are the industry standard because, in some cases, it is possible to recreate a hydrodynamic effect using lubrication [15, 17]. This allows the workpiece to practically glide along the die with very low friction. Yet, the byproduct waste of liquid lubricants is harmful to the environment encouraging industry to look for alternatives. Solid lubricants are being explored as alternatives, but they perform differently in experimental conditions versus under actual forging conditions [13, 16, 18, 19]. When using solid lubricants, it has been shown that using a double layer is as effective as liquid lubricants but nuances in the application include the surface finish of the tool and determination of the best film thickness [15]. This demonstrates that the results of lubrication studies are impacted by the significant variety of parameters that influence the performance of lubrication such as applied pressure, workpiece surface expansion, deformation velocity as well as others. Varying only one parameter of the forging process at a time is practically impossible making isolated analysis of the effect of lubrication on friction difficult. Additionally, interest in dry forging, or forging without lubrication, is increasing because of the negative impact some lubricants have on the environment as well as potential reduction in costs that this would produce [9, 10]. Therefore, it is important to explore other factors that affect the friction value.

Forging Pressure

Pressure is important to account for when calculating the coefficient of friction. Enough pressure must be applied to the workpiece for it to deform, also described as the applied pressure surmounting the yield strength of the material. Depending on the amount of pressure applied to the workpiece, some friction models can be more accurate than others because friction conditions at high contact pressures have been found to differ greatly from low contact pressures [5, 9]. There seems to be a non-linear increase in frictional stress on the workpiece as normal pressure increases, with the stress increasing more rapidly at lower pressures than higher pressures [18]. Even then, friction equations have difficulty predicting friction occurrence at the initial step of the forging process [8, 17]. Since the first application of pressure incurs a large amount of stress on a much more limited area of the workpiece than in later steps, the actual friction value at the tool-workpiece interface is difficult to estimate [19, 20]. This is related to the contact pressure distribution across the workpiece which is an influential factor on the coefficient of friction at each stage of the forging process [5, 20, 21]. Depending on the non-uniformity of the distribution of pressure, the friction coefficient changes and it becomes harder to model due to its unpredictability. Illustrated in Figure 3 are the changes in contact pressure distribution throughout the entirety of a forging process, indicating how the coefficient of friction is subject to change alongside it.

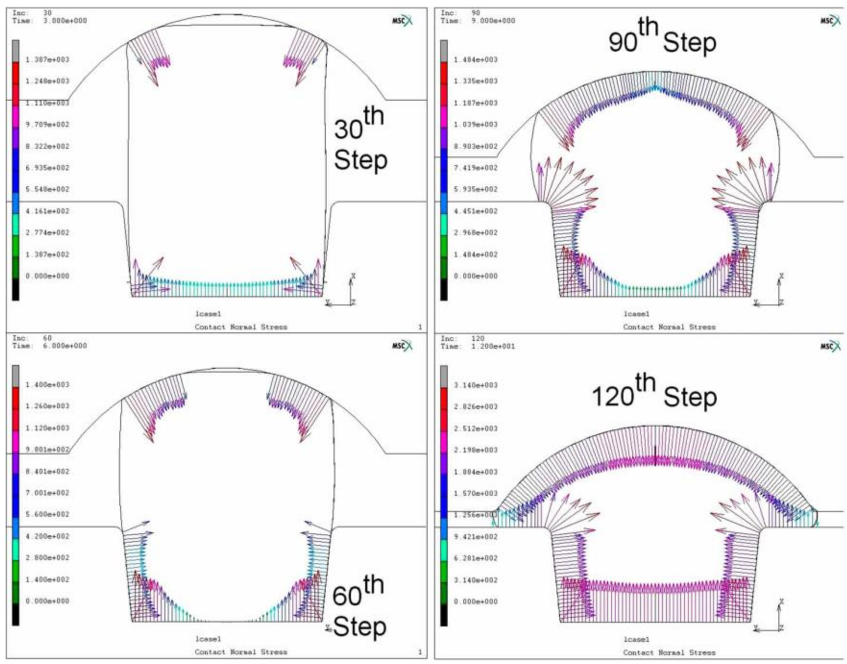

Figure 3. Vector plot of contact normal stress [5]

Included in this category is forging load, which is a derivation of pressure. Forging load is the amount of pressure that is applied to the workpiece accounting for its geometry in addition to material properties, meaning it changes throughout the forging process [8, 21]. Thus, the load required is difficult to determine during multi-stage operations, even for symmetrical parts [8]. As the material flows through the die, the load also increases depending on the angle of the contact pressure incurred from the die. The greater the die angle, the more forging load is needed for the material to flow through the die while resisting the friction occurring at the die-workpiece contact surface [8, 14]. Therefore, the load has an influence on other variables of the forging process such as surface stress and surface roughness, both of which impact the quality of the finished product as well as increased tool deformation on account of friction [5, 10, 17].

Surface Topography

In this case, surface topography primarily refers to the roughness of the forging die surface. This has been the subject of several studies investigating the correlation of surface roughness and friction [2, 11, 12, 16]. When a significant amount of friction is present generating wear at the die-workpiece interface, material begins to be chipped away causing asperities or cavities to form on the tool thereby increasing the surface roughness [14]. This has a negative effect on both the quality of the forged product, whose finish can become uneven, and the lifetime of the die, by initiating cracks in the surface [10]. Therefore, other experiments have explored the effects of roughness on premature die wear as a result of friction [10, 22] as well as the preferred surface roughness for forging operations [2, 21]. Currently, research shows that both polished and grounded tool surfaces cause less adhesion with the workpiece and therefore, a smaller coefficient of friction [2]. Tools with high surface roughness were also found to prematurely break more often, with much of the fault related to the initial topography of the tool [10]. However, different regions of the tools experience different rates of wear making the effect on friction, tool life, and workpiece quality difficult to monitor [7]. Yet, it is important to determine what kind of surface topography is best at least in regard to other parameters. It has been found to influence the performance of lubricant as well which, as previously stated, has a great impact on the coefficient of friction and tool life [11, 16, 22, 23].

Figure 4. Types of die surface topographies [24]

Part Geometry

The geometry of the part largely determines the type of forging that will be used to produce it. Cold forging is frequently used to produce parts with complex and unusual dimensions due to the tight tolerancing, or accuracy, it can achieve [3, 4]. Because of this, it is important to consider the part geometry when calculating the coefficient of friction. Part geometry influences both the modelling of friction as well as the occurrence of friction in the forging process. Theoretical friction models are based on real contact area, which constitutes a small portion of the apparent contact area [5, 9]. This real contact area is largely dependent on part geometry and its interaction with the surface of the die. For example, the higher the surface enlargement—or change in area—of the workpiece, the higher the friction coefficient will be because a greater part of the die-workpiece surfaces are interacting with each other [4, 17]. Similarly, the ratio of contact normal stress to equivalent yield stress is dependent upon the distribution of stress across the part geometry [5]. This effects friction modeling by causing large variations in the friction coefficient throughout the extent of the forging process. Thus, variable friction models are preferred when part geometry is irregular [5]. However, part geometry also impacts the forging load required due to the creation of different deformation zones. Each deformation zone experiences a different amount of stress because the changing part geometry affects the real contact area, requiring calculation differences for the forging load and coefficient of friction of each zone [8, 9, 20, 21].

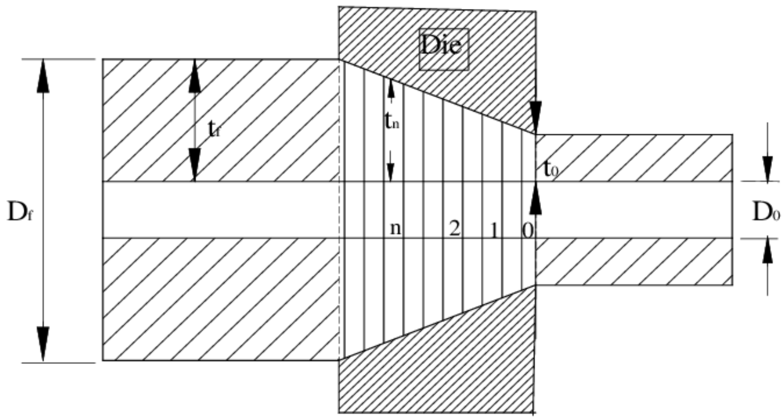

Figure 5. Illustration of deformation zones (0,…, n) [22]

Tool-Workpiece Interface Temperature

While cold forging is performed at room temperature, during metal formation, there is a release of forming and friction energy as heat. This, in combination with high outputs in a short amount of time, can result in die-workpiece interface temperatures starting at 200ºC [2, 17, 25]. The amount of heat released depends on the forming load required and the amount of friction generated as a result of the aforementioned conditions such as surface topography, forging pressure, and deformation velocity [10, 17, 19]. Higher coefficients of friction resulting from rougher surface topographies combined with greater velocities, for example, can increase the interface temperature because more energy is created between the contacting surfaces to overcome their resistance to movement. However, the resulting rise in tool-workpiece interface temperature can simultaneously impact the performance of lubricants thereby increasing the coefficient of friction further [17, 18]. Therefore, when evaluating lubricant performance, it is important account for the rise in temperature as well as the thermal equilibrium in which most of the process takes place [17, 19].

Deformation Velocity

Deformation velocity in forging, or speed with which load is applied to the workpiece, depends on the type of part being produced and the type of forging method used (extrusion, drawing, etc.). In developing friction models, scientists have studied the effects of velocity extensively particularly on the dynamic stability of frictional systems or a processes ability to return to a steady state [7]. Studies have shown that the friction coefficient decreases as relative velocity increases [7, 17, 25]. This could be due to the fact that the asperities on the surface of the die and the tool don't have enough time to catch at one another when high speeds are in use. Velocity can thus potentially reduce adhesive wear on the die itself, but tool-workpiece interface temperature is negatively affected with the rise in velocity [17, 25]. However, since the quality of a forged part depends on the smoothness of metal flow as well as the lack of friction, velocity can be a key factor in regulating friction during forging.

Material Properties

The material properties of both the forging die and the workpiece influence not only the formation of friction during forging, but also other forging conditions themselves that lead to changes of the coefficient of friction. Material properties of the workpiece determine the forging load required for the process to be completed based on the yield strength of the material [21]. As previously described, forging load has been shown to affect friction during forging. Many friction models consider only the yield strength of the workpiece based on its material properties, instead of the state of stress at the time of forging [5, 9]. Similarly, the material flow of the metal has been found to impact the asperities formed during the process which alter the coefficient of friction [2, 9]. This is due to the positive correlation between the flow stresses and contact stresses a workpiece experiences. Higher flow stresses generate higher contact stresses, causing greater adhesion of the workpiece to the tool and, in turn, causing an increase in friction [2, 8].

How the forging die is made and from what material needs to be considered as well, as studies have shown that the type of manufacturing method can have an impact on die performance. Particularly, the method influences the tool's surface conditions and resistance to stress during the forming process [10, 11]. As previously mentioned, surface roughness can increase the generation of friction when the tool and metal interact [2, 10, 17, 22]. Meanwhile, increased resistance to stresses can help the tool with withstanding the cyclical loading it is subject to during the process and decrease the rate of adhesive wear on the tool caused by friction [10, 11, 22].

Analysis of the Dependency between Friction and Forging Conditions

A literature study was conducted on friction models and experiments of the forging process presented in the last 15 years. This time frame was chosen because forging is a well-established process with most of the research focusing on improvements, rather than novel changes, ensuring that the ensuing discussion of modeling techniques and experimental results remain relevant in the field. The studies were analyzed for their findings on what factors seemed to affect the presence of friction during the forging process. The variables and assumptions used in friction models were also evaluated for their accuracy in predicting the coefficient of friction. Based on this literature study, the following table was developed to summarize the interdependency of forging conditions that have been shown to affect the occurrence of friction during the process.

Forging Condition	Lubrication	Forging Pressure	Surface Topography	Part Geometry	Deformation Velocity	Interface Temperature
Lubrication		X	X	X		X
Forging Pressure	X			X		X
Surface Topography	X					
Part Geometry	X	X				
Deformation Velocity						X
Interface Temperature	X	X			X	

Figure 6. Interdependency of forging conditions affecting friction

These interdependencies show that friction during forging is difficult to predict because of the many parameters that are accounted for in the process. While some conditions directly influence another causing a change in the friction value, others have been shown to vary in their correlation depending on the constraints of the experiments and complexity of parts. Adding to the challenge is the fact that many of these conditions cannot be tested by themselves for their effect on the coefficient of friction because they are dependent on another. This restricts the evaluation of the severance of these interdependencies due to lack of sufficient data that evaluates each specific interdependency at a time. However, future research on this topic can be guided by the basis for the conclusions and creation of Figure 6 as described below.

Lubrication and Forging Pressure

As previously mentioned, poor lubrication increases the forming load because of the greater amount of friction that is needed to overcome during the forging process [10, 11]. Experiments have also demonstrated the significant influence of normal pressure on friction stress caused during forging, regardless of the type of lubricant used [18]. However, the amount of friction increase is dependent on the lubricant properties [13, 18]. It has also been observed that the lubricant's response to contact pressure can be different at various temperatures [17, 19]. With this information, it has been found that lubrication is most effective when the least possible amount of quantity of lubricant is used. Too little causes too much frictional stress on the die and workpiece because the great amounts of pressure the workpiece is subject to during forging can sweep away the lubricant leaving the die and workpiece prone to adhesion [10, 14]. In turn, this can also increase the surface roughness—another factor that contributes to the increase of friction and the reduction of tool lifespan. As the forging load is increased, the surface roughness of lubricated workpieces changes less than that of unlubricated pieces [10]. Yet too much lubricant causes uneven surface quality and reduces the parts dimensional accuracy [14]. In fact, after the minimum lubricant quantity is applied, forming load and contact pressure increase for each increase in lubricant amount causing a simultaneous increase in the coefficient of friction [14].

Lubrication and Surface Topography

It is important to consider the surface topography of the die and the workpiece when determining the amount of lubricant that should be applied. The surface topography of a tool accounts for its roughness, which can otherwise be estimated by the number of cavities in the tools surface. During lubrication, it is difficult to determine when all cavities of the tool have been filled with lubricant, especially if the cavities are of different sizes as commonly occurs due to the continuous deformation of the tool over its lifecycle. Rougher surface topographies cause loss of lubricant in the cavities of the tool and an overall uneven layer of lubricant, both of which cause greater adhesion to occur during forging [2, 11, 16]. This is supported by findings of fine blasted tools having lower friction coefficients [2, 10, 16]. However, there is a fine line between a surface being too rough and not rough enough. Roughly ground surfaces have 21% lower friction coefficient than polished surfaces [2], most likely due to the high friction values smooth surfaces experience. Pre-lubrication of the tool has been found to work very well with fine blasted tools for decreasing friction by balancing the lubricant loss and intake [2]. Loss of lubricant is minimized because cavities are more regular and not as deep thereby requiring a smaller amount to be applied. This is beneficial because the use of more lubricant to fill the cavities is negatively reflected on the overall cost of the process so the surface finish of tools is important to consider.

Considering the type of lubricant used in the process dictates the optimal surface roughness to be used [13, 14]. A study found that the anti-galling abilities of solid lubricants are highly sensitive to the surface roughness of the workpiece. During multistage operations, the lubricant can be stripped off during the initial phase if the surface is too rough and not provide sufficient protection against friction in subsequent forging stages [11, 13]. The performance of the lubricant was highly improved when the workpiece was pre-treated by wet blasting, which refines surface finish and allows the lubricant to adhere to the workpiece better [13, 15]. The tools also showed comparable performance to liquid lubricants in terms of the value of the coefficient of friction obtained during experiments [13, 15].

Proper lubrication can reduce the increase of surface stresses of the tool and the workpiece because it creates an additional layer of protection against adhesion when the two interface [10]. Workpiece surface smoothness has been shown to be highly dependent on the used lubrication system so lubricant-specific sticking friction should be accounted for during modeling to obtain accurate stress values [16]. Often, film thickness has to be modified depending on the compatibility between the type of lubricant and surface roughness [10, 15]. This is also observed when comparing the influence on resulting surface roughness of dry versus lubricated contact surfaces [14]. Without the protectant lubricant layer, the workpiece deforms to mimic the surface roughness of the tool itself while simultaneously forming more cavities in the surface of the workpiece due to the high friction stresses that arise.

Lubrication and Part Geometry

Studies have shown that accumulation of lubricant on the tool surface can decrease the coefficient of friction [2, 6]. This accumulation can depend on the geometry of the part being formed. Particularly during extrusion forging, in which the part is fully enclosed by the forging die and experiences high contact normal stresses, it is difficult for lubricant to escape during the forming process. Thus, it accumulates around the contact zone prolonging the effects of the lubricant on the coefficient of friction [6, 9]. This effect is often not considered in friction tests and models but should be accounted for as it effects the accuracy of predicting the occurrence of friction. Additionally, the extent of surface expansion during the formation of the part has been shown to play a role in the effectiveness of lubrication [4, 6, 15]. This might be due to the fact that surface enlargement affects how much friction the part experiences during the process. It was found that when using even solid lubricant, increasing the lubricant film amount proved to be more effective at protecting the part against the effects of friction [15]. Consequently, it is important to account for surface enlargement when determining the amount of lubricant to apply. This can result in lower friction coefficients and more accurate part dimensions as a result of more ideal lubrication conditions that correspond to part geometry [4].

Lubrication and Interface Temperature

Most friction models do not account for the change in temperature that occurs during the forging process as a result of the forming and friction energy generated. This can lead to inaccuracies in theoretical coefficients of friction in comparison with experimental values because this change in temperature can provoke a change in lubricant viscosity. The rise in temperature can lower lubricant viscosity allowing it to spread out more easily and uniformly across the workpiece [16]. Especially for solid or dry lubricants, viscosity can significantly be reduced with increasing temperature [4, 16, 17]. Once the solidus temperature is reached, or the temperature at which a solid compound starts taking on liquid properties, the lubrication effect is improved because the change in properties leads to an increased and uniform spread of lubricant across the workpiece. In fact, using lubrication that has high resistance against temperature rise and therefore unable to take on liquid properties can be detrimental to multi-stage forging processes because it lacks anti-galling ability and is easily stripped from the workpiece [13]. It is interesting to note that effective lubrication also reflects on the temperature change itself, with heat generation becoming primarily due to deformation instead of friction [17]. This highlights the interdependency of these two conditions which should be accounted for more often in models and experiments. However, the workpiece-die interface temperature should not be artificially altered by heating up the forging die. This, instead, has shown to negatively influence the performance of lubricant, resulting in flaws and dimensional inaccuracies of the forged parts [11].

Forging Pressure and Surface Topography

When high surface stresses occur with increasing forging loads, asperities on the surface of the tool or workpiece can start to occur faster resulting in the increase of surface roughness and thereby the coefficient of friction as well [8, 10]. Many experiments have demonstrated this positive relationship between the forging load and surface roughness. Forming load increases with surface roughness in turn increasing the coefficient of friction and causing a coarser surface finish of the finished product [10, 11, 14, 16]. The coarse surface finish may result from the wear generated by the increased friction on the contact surface causing debris to form [14]. The need to overcome the friction from surface irregularities caused by the debris accumulation simultaneously increases the load and negatively affects the material flow, potentially leading to cracks in the product later on [10, 16]. As a solution, lubrication can help reduce the increase in surface roughness of the tool and forging load as long as the proper kind of lubricant is chosen as was indicated in previous sections.

Forging Pressure and Part Geometry

The interdependency of part geometry and forging pressure is most directly emulated by the geometry's impact on pressure distribution. During the forging of complexly shaped parts, the coefficient of friction values could change significantly throughout the process. Immigrated contact area, which is constantly changing as the part is formed, can increase the coefficient of friction [5]. Due to the changing shape of the part as well as the difference in pressure application at various deformation zones (exemplified by Figure 5), especially for bulk forging operations, significant variation of friction coefficient values over the contact surface and by punch displacement has been experimentally shown [5, 8]. This makes the prediction of friction challenging when using constant friction models because of the large disparities in the contact pressure distribution [5]. More uniform contact pressure can be achieved, but it requires a larger contact area between the die and the workpiece, which the complex parts that cold forging is used for often lack. Understandably, part geometry is a set constraint that can't be changed but variable friction models can be used when contact pressure isn't uniform and the real contact area is constantly changing, as such is the case for irregular part geometry (i.e. complex parts), to predict friction more accurately [8, 9].

Deformation Velocity and Interface Temperature

The interface temperature during forging between the die and the workpiece has been shown to be strongly linked to the deformation velocity of the process [7, 17, 19, 25]. This is because higher drawing velocities lead to higher coefficients of friction as the process occurs at a faster rate and more energy is generated. The higher coefficient of friction contributes to increasing the interface temperature because more heat transfer occurs. Maximum temperatures usually occur in areas of direct contact between the forging die and the workpiece where the surface enlargement is greatest due to the corresponding heightened frictional energy dissipation [17, 18, 19].

However, the friction value has been shown to significantly decrease, up to 66%, due to the rise in interface temperature [17, 19]. This is because as temperature rises, the viscosity of the lubricant is lowered helping it to spread out uniformly across the contacting surfaces [19, 25]. Additionally, particularly for solid lubricants, the higher temperatures help with the activation of intra-film lubrication further facilitating smooth workpiece formation and decreased friction values [19]. Experiments do show that a certain temperature is required to be reached to start observing a decrease in the friction coefficient [25]. For solid lubricants, this temperature begins when the lubricant starts to take on liquid properties allowing it to be more effective in multi-stage operations. Accounting for and controlling the actual temperature at the tool–workpiece interface can provide insight into improving cold forging operations by aiming for ideal temperatures specific to the applied lubricant and forging process.

Recommendations for Reducing Friction

Analysis of the aforementioned interdependencies in future experiments can lead to a better understanding of friction as a multidimensional variable of the forging process. It can also point out the areas that need to be focused on for improvement of the overall process and which forging conditions should be monitored concurrently during experiments. The table below briefly summarizes the main causes and effects of friction increase as an expansion of Figure 6.

Effects / Causes	Friction Increase Due To				
	Contact Pressure Increase	Forging Load Increase	Surface Roughness Increase	Tool - Part Adhesion Increase	Lubricant Effectiveness Decrease
Forging Load Increase			X		
Surface Roughness Increase		X		X	X
Adhesion Increase			X		
Surface Enlargement Increase					X
No/Poor Lubrication	X	X	X	X	
Excessive Lubrication	X	X			
Untreated Tool Surface		X	X	X	X
Polished Tool Surface				X	

Figure 7. Main causes and effects of friction increase

Based on these findings, the following recommendations for reducing the coefficient of friction experienced in cold forging can be made.

1. Forging tools should be pre-processed to achieve fine-blasted surface topography.

This will improve the adhesion of lubricants [2, 10, 16] increasing their effectiveness and decreasing the coefficient of friction. This might also reduce the amount of lubricant required and consequently reduce overall costs associated with the process [11, 13, 15].

2. Forging tools should be pre-lubricated, regardless of the lubrication of the workpiece.

This has been shown to significantly reduce the coefficient of friction [2, 6, 10] and be particularly helpful in multi-stage operations where long-lasting staying properties of lubricant are preferred yet difficult to achieve due to it easily wearing off with high contact pressures. Increased effectiveness of the lubricant will further lead to decreased forming load, improved workpiece surface finish, and uniform part geometry, which are all affected if high friction values are present.

3. Only the minimum quantity of lubricant required should be determined for each lubricant type and applied.

Minimum amount of lubricant application has been shown to be the most effective at reducing friction during the forging process [14] because both too little and too much lubricant negatively affects other forging conditions that are critical to generating friction. The amount applied depends on the type and chemical composition of the lubricant, as well as the forging conditions it will be subject to. Perhaps determining a standard application amount for each lubricant type and forging process will provide industry with a streamlined way to reduce friction coefficient values.

4. Variable friction models should be favored in simulations and experiments.

Variable friction models have consistently been demonstrated to achieve closer coefficient of friction values to experimental results [5, 9, 12]. While there are more factors that need to be accounted for, by making this the industry standard for modelling friction, comparison of experimental test results would be possible. This would pave the way for consolidation of research findings to achieving a better understanding of what exactly influences the occurrence of friction.

5. Interdependency of lubricant with other forging conditions should be accounted for in forging operations and experiments.

Since lubricant is dependent upon many other variables of the forging process, it is critical that these factors are included in simulations and in industry operations as well. For example, the effect of the die-workpiece interface temperature is not often accounted for, yet it has been shown to drastically affect the lubricant properties [18, 19]. Interdependencies such as these will be useful in determining the minimum amount of lubricant that should be used, in accordance with recommendation 3, to help with reducing the coefficient of friction.

Overall, the research present aims to serve as a guide for determining which parameters of the forging process affect the occurrence of friction. The recommendations that have been made aim to guide future research in evaluating their effectiveness at reducing friction and determining shortcomings in industry use. By decreasing the friction that occurs during forging it will be possible to prolong the lifetime of forging tools, decrease costs, and maintain the high quality of forged parts.

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