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Review Article

A Review on Galling of Aluminum in Cold Forming Processes

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ABSTRACT

As world's sustainability becomes the most influential topic, aluminum and its alloys are becoming the preferred material of the automotive industry because they allow vehicle weight to be reduced without compromising safety. Thus, aluminum has taken its place in the global industry as an alternative material that can be used instead of steel. The main drawback of forming aluminum at room temperature is galling. This phenomenon in cold forming of aluminum not only affects the quality of the produced parts but also the lifespan of production tools. This paper reviews the galling of aluminum alloys during bulk and sheet cold forming processes along with friction conditions. The available testing methods in order to simulate the actual cold forming process are introduced. Effect of process parameters such as lubrication, tool surface finish and tool coatings are discussed in detail.

Keywords: *Galling, Aluminum alloys, Cold forming*

Soğuk Şekillendirme Proseslerinde Alüminyumun Yapışma Aşınması Üzerine Bir İnceleme

ÖZ

Sürdürülebilirlik dünyanın en etkili konusu haline gelirken, alüminyum ve alaşımları, güvenlikten ödün vermeden araç ağırlığının azaltılmasına olanak sağladığı için otomotiv sektörünün tercih edilen malzemesi haline gelmektedir. Böylece alüminyum çelik yerine kullanılabilecek alternatif bir malzeme olarak küresel endüstride yerini almaktadır. Alüminyumun oda sıcaklığında şekillendirilmesinin ana dezavantajı yapışma aşınmadır. Alüminyumun soğuk şekillendirilmesindeki bu olay, yalnızca üretilen parçaların kalitesini değil, aynı zamanda üretim takımlarının ömrünü de etkiler. Bu çalışmada, sürtünme koşullarıyla birlikte kütlesel ve sac soğuk şekillendirme işlemleri sırasında alüminyum alaşımlarının adhesiv aşınmasını incelemektedir. Gerçek soğuk şekillendirme sürecini simüle etmek için mevcut test yöntemleri tanıtılmaktadır. Yağlama, takım yüzey kalitesi ve takım kaplamaları gibi proses parametrelerinin etkisi detaylı olarak tartışılmaktadır.

Anahtar Kelimeler: *Yapışma aşınması, Alüminyum alaşımları, Soğuk şekillendirme*

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I. INTRODUCTION

Human activities throughout the centuries impacted the world that we live in. Among these, global warming became one of the most influential topic in recent years where carbon dioxide (CO_2) content in the atmosphere increased by 50% in less than 200 years ago. Naturally, countries took precautions to prevent the emission of more CO_2 into the atmosphere and released stringent legislative regulations. These precautions motivated companies to push their limits for innovative ideas to find carbon free alternatives for already existing applications. In this sense, automotive industry has focused on electric vehicles to overcome these regulations and contribute to world's sustainability. A report from the mobility of the future study by MIT Energy Initiative [1] revealed that an average CO_2 emission for petrol car is at least 350 gr where it decreases for hybrid cars around 260 gr per mile. Best carbon emissions are observed for fully battery-electric vehicles with only 200 gr. This shows that we can significantly decrease the carbon emission by only changing the type of fuel. However, electric cars have their own downsides and the biggest problem to be solved in these vehicles is the driving range. The simplest solution for such problem is to reduce overall weight of the car. This has two significant effects: firstly, many forces acting on a vehicle are directly related to its weight. A decrease in mass diminishes required driving force and thus yields to reduced energy consumption. Secondly, a lighter car is considered safer due to its lower inertia, meaning that it needs a shorter distance to halt than its heavier alternative [2].

The weight reduction is generally related to the material change and especially in lightweight cars; aluminum alloy is the main material choice [3-5]. Aluminum alloys possess a desirable combination of characteristics, including extended durability, low weight, high strength-to-weight ratio, malleability and exceptional resistance to corrosion. Additionally, 95-98% of aluminum can be recycled repeatedly with a high quality, which is another important criterion for sustainability [6]. Due to these desirable properties, many lightweight car designs and parts, in Figure 1, are introduced with already existing or improved aluminum alloys [7-8].

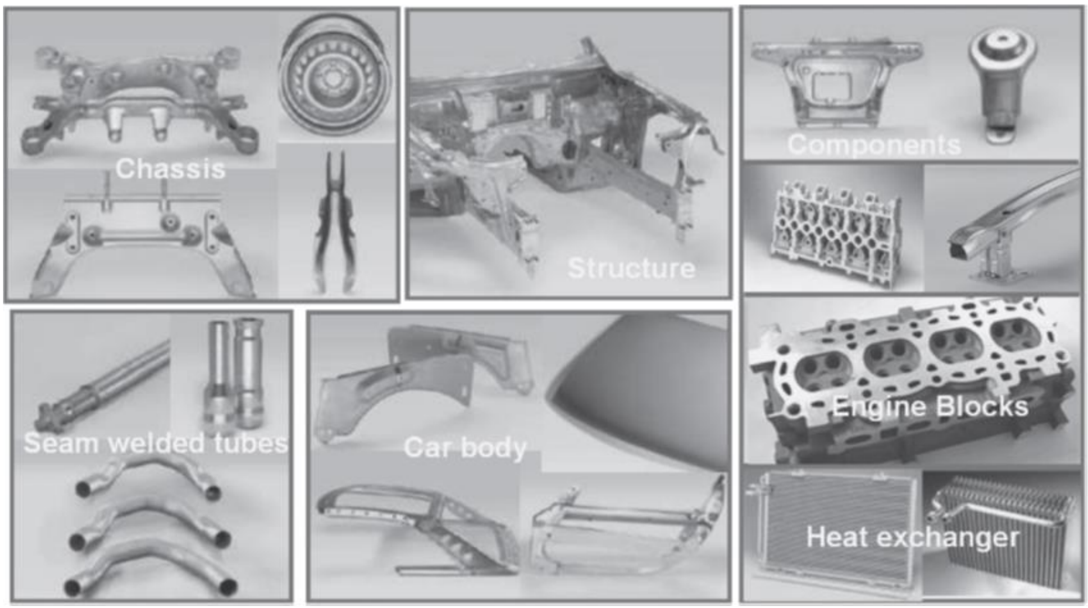

Figure 1. *Aluminum alloy applications for light-weight cars[9]*

Wrought alloys are classified into a two specific groups. First one is the non heat treatable alloys in which solid solution, strain hardening and dispersion hardening are the main methods to get required strength enhancements. This group consists of 1xxx, 3xxx, 4xxx and 5xxx series alloys. Other group is heat treatable alloys and their strengthening mechanisms are solution heat treatment and controlled aging. This group includes 2xxx, some of 4xxx, 6xxx and 7xxx series alloys [10]. Within aluminum alloys, 6xxx group have been widely researched due to its favourable properties such as heat treatability, robustness and weldability. When all 6xxx series aluminum alloys compared, it can be seen that the 6082 alloy within this series is the most common one due to its attractive properties such as higher mechanical properties, excellent corrosion resistance and convenience for T6 aging [11]. Wrought aluminum designation system with major alloying elements and their features is given in Table 1.

Table 1. *Wrought alloy designation system [10]*

Alloy Series	Major Alloying Element	Features
1xxx	Pure aluminum, 99%	Electrical conductivity
2xxx	Copper	Increased strength
3xxx	Manganese	Food safe
4xxx	Silicon	Lower melting point
5xxx	Magnesium	High corrosion resistance
6xxx	Magnesium and Silicon	Heat-treatable
7xxx	Zinc	High Strength

Metal forming is broadly used in automotive industry to manufacture parts with various size and shapes by plastically deforming the materials. This plastic deformation can be categorized into two group as bulk deformation and sheet metalworking with their own sub-groups [12]. Among the bulk deformation tecniques, forging is the most common metal forming technique, which uses compression forces in order to shape the work piece material between dies. Traditional forging is classified as hot, warm and cold forging according to application temperature. Cold forging is performed at temperatures below the recrystallization temperature of the work piece material, generally at room temperature, while hot forging is performed at temperatures above it. Warm forging is carried out at the temperatures between hot and cold forging application temperatures. The mentioned forging techniques have advantages and disadvantages compared with each other. In order to produce machine parts with hot forging, the work piece must be heated up to a certain temperature and this heating causes additional energy consumption. On the other hand, forging loads required to plastically deform the material decreases significantly and risk of damage in the work piece minimizes with the heating of the material. Better mechanical properties in the final product can be obtained with the cold forging thanks to the phenomenon of strain hardening. In addition, cold forging is a net-shape-forming technique, so generally there is no additional process required to obtain final shape of the product. In addition, this technique is suitable for mass production [13,14]. Due to these favourable properties, many vehicle parts such as nuts, bolts, bushes, joints and many more are manufactured by this forming method.

Despite its beneficial mechanical features, cold forming of aluminum is a challenging process due to its complicated nature. For instance, aluminum has tendency of sticking to tools during a cold forming process that can decrease the overall quality of the manufactured part. The work piece material that sticks to the tool surface undergoes hardening through oxidation, work hardening and grain refinement during the operation. Subsequently, it scratches the softer work piece material throughout the rest of the forming, which is commonly known as galling [15]. An example is shown in Figure 2. As a result of galling, surface finish of the manufactured parts deteriorates [16,17] and even in some severe cases, it can abrade the tool itself. There are many effecting factors on galling such as temperature, surface roughness, lubrication, sliding distance and contact pressure [18,19].

Figure 2. *Cylinder that galled on removal from a conforming cylinder [20]*

In literature, the majority of the studies related with cold forming of aluminum alloys are focused on the galling and the friction conditions between work piece and cold forming tool. In this review, the examination of the galling phenomenon in aluminum alloys is presented within the context of bulk and sheet cold forming processes, along with considerations of friction conditions. Various testing methods designed to simulate the cold forming process are also presented. Furthermore, the review delves into a detailed discussion of the effect of process parameters, including lubrication, tool surface finish and tool coatings.

Heinrichs and Jacobson (2009) investigated the effect of surface parameters on the tendency of galling during forming of aluminum using tool steel in laboratory tests. In this study, the parameters were selected as tool material, tool surface roughness and work piece surface preparation. AA6082 (1.2 %Si and 0.8 Mg), aluminum alloy, was used as a work piece material and samples were prepared by two different pre-treatments. First, aluminum samples were soft annealed, lubricated and extruded to 100 mm long cylinders with a diameter of 10 mm. Then, in order to obtain different surface quality, extruded cylindrical rods were separated into two equal groups. First group was soft-annealed and lubricated again whilst second group was only pickled. After these preparations, hardness of the soft-annealed and pickled samples were measured as 35 HV and 60 HV, respectively. To simulate the galling and the friction conditions between the work piece and the tool during cold forming, a load-scanner equipment was used in the sliding-contact tests. Brief illustration of their test set up is illustrated in Figure 3. Principle of the test was as follows, tool steel slides over the aluminum samples and deforms the contact surface. This sliding motion was performed in two different parts as single and multiple strokes. Then, contact surfaces were investigated by using scanning electron microscopy. The procedure was followed for both pickled and lubricated surfaces. Current testing method is proved to be an effective way to examine galling of various tool steels and is used in other studies as well [21,22]. Authors concluded that lubrication significantly effects galling. Experiments revealed that unlubricated surfaces were susceptible to galling even in the smoothest tool surfaces and it cannot be avoided. Similar outcome was obtained for the cases where lubrication wears off and maximum friction coefficient increases immediately. Another finding was about the occurrence of galling. It can be observed in both smooth and rough surfaces as thin layer and/or lumped together where aluminum transfer (galling) was not necessarily a function of high friction coefficient. Around the scratches in rough tool surfaces galling occured in which aluminum deposits in and over these surface impurities. Thus, author suggested that in the forming process of aluminum, tool materials with smooth surfaces and proper lubrication were key parameters in terms of alleviating the adhesive wear [23].

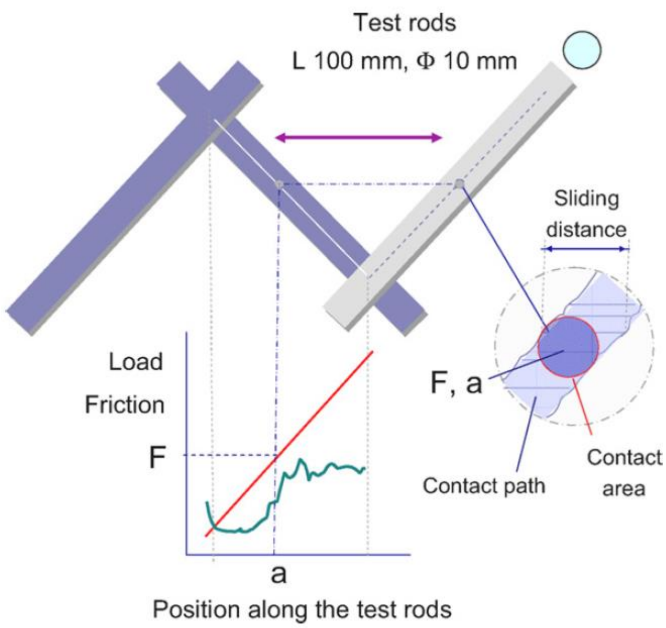

Figure 3. *Sketch showing the test set up [23]*

Heinrichs and Jacobson (2010) investigated the effect of coating on the AA6082 aluminum's tendency of galling during cold forming. Various coatings, namely diamond like carbon (DLC), titanium aluminum nitride (TiAlN), titanium nitride (TiN) and titanium carbonitride (TiCN), were applied on 8 tool samples by using physical vapor deposition (PVD) technique as single layer or as multilayer combinations and compared with the uncoated tool. Briefly, these coatings are widely used in industrial applications for their superior characterictics such as high hardness, low friction, chemical inertness and self-lubrication. Due to these qualifications, they are widely used in forming and machining of metal parts [24-28] and special attention is given to it in this study. Coatings like TiN, TiCN, and TiAlN are generally used for tool life and performance purposes by decreasing the friction between work piece-tool contact in the literature. Technical data about the applied coatings in the paper are given in Table 2.

Table 2. *Main alloying elements and hardness of the tested tool steels [29]*

Tool steel	**Steel type**	**Hardness** *(HRc)*
Grade A	5Cr-Mo-V	50
Grade B	5Cr-Mo-V	55
Grade C	9V,4.5Cr-Mo-W	60

Influence of different coatings were examined by comparing results of the tests with uncoated tool. H13 was selected as tool material and two sets of tools were prepared in which the first group has higher roughness while other tools have smoother surface. Regarded surface roughnesses of the tools are given in Table 3.

Table 3. *Roughness parameters of the rougher surfaces (white light interferometry) [29]*

	Mean Ra *(nm)*	**Mean Rt** *(nm)*	**Mean Rq** *(nm)*
Grade A	280	2900	350
Grade B	270	3200	340
Grade C	250	2900	310

The AA6082 samples were prepared with two different pre-treatment same as the authors previous study [23] and tests were carried out by using a load scanning rig. Conducted tests revealed that there is a significant difference between pre-lubricated and unlubricated pickled aluminum samples in the sense of friction performance. The effect of tool roughness was minimal in pre-lubricated aluminum rods and in some cases coating performance was same with the uncoated tools. On the other hand, some of the DLC coatings in unlubricated and pickled aluminum samples yielded to maximum performance in comparison by keeping low friction for more than 200 strokes. For the same conditions, other coatings and uncoated tools could keep low friction for less than 10 strokes. The occurence of galling under high loads was also different in pre-lubricated samples where aluminum deposition observed as large bulky flakes on top of the tool rod where it was more integrated with the surface in pickled ones. In any circumstances the lubrication was found as the most important factor in terms of galling and friction conditions. Authors also highlighted that there is no clear correlation between hardness of the coating and the aluminum's galling tendency. Coatings with a higher hardness than aluminum oxide could or could not mitigate aluminum adhesion which leads to a unreliable outcomes. Even in combination of hard coating with a smooth surface could fail to prevent galling which shows that the chemical adherence is also an important parameter [29].

In order to examine the effect of tool defects on occurrence of galling, Heinrichs and Jacobson (2011) conducted another study. They used two layered DLC coated tools, first layer was Me-Doped and the second layer was hydrated DLC. Controlled defects with various sizes on the tool surfcaes were created with Berkovich, Vickers and spherical diamond tips. In order to create less controlled defects SiC grinding paper was also used. Illustration of these surface defects are given in Figure 4. They followed same experimental procedures with their previous studies where sliding-contact test wih a load scanner equipment was used for investigating the galling and the friction conditions. AA6082 and AISI H13 were selected as work piece and tool material, respectively. The aluminum samples were not lubricated to get worst contact conditions possible. The tool materials were prepared with six different depts, scaling from nano to micro scale and one sample was left polished for comparison. Results of the sliding-contact test revealed that the effect of surface irregularities was negligible in the sense of friction coefficient at the first stroke. But, scanning electron microscope (SEM) image of the tool surface showed that aluminum was deposited inside dents which could excite galling in following strokes. Authors examined the transferred aluminum to tool by using electron spectroscopy for chemical analysis (ESCA) and found that transferred aluminum was mostly in the form of aluminum oxide and could not cover the whole tool surface. This could be achieved only if aluminium was transferred gradually while sliding, with each thin film being extensively oxidized before the subsequent film was transferred. One interesting finding was the hardness increment of deposited aluminum. Before experiment, hardness of the aluminum sample was 60 HV. After first stroke, it increased to 65 HV and after multiple strokes it became 95 HV. Authors explained this occurrence by mechanical entrapment of aluminum inside the dent. In first stroke, aluminum deposited into the dent in a blotchy manner. Then, rod slided back along the path and removed the tip of deposited aluminum while remaining metal was trapped inside the dent. This removing process highly sheared the top surface of trapped aluminum in which the metal was plastically deformed and authors believe that this repetitive passage could harden the aluminum. Even though these dented areas increased the friction locally, they had insignificant effect on the overall friction. In brief, the results of the study emphasized that the adherence of aluminum on the tool surface initially occurs around the scratches, and with a good surface finish of the tool, it can be avoided. However, this initial adherence didn't have a significant effect on tool life compared to overal surface finish [30].

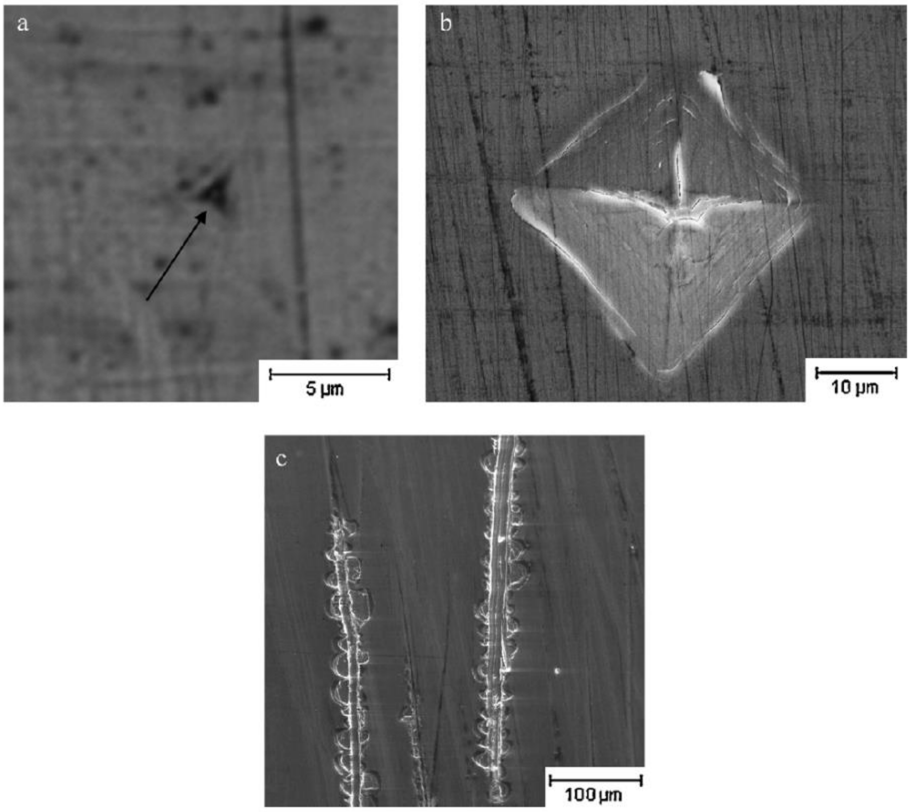

Figure 4. *Image of (a) nanoindentation with depth 160 nm (optical microscopy), (b) microindentation with depth 5.6 μm (SEM) and (c) scratches from 240 grit paper on the surface of a coated tool rod. [30]*

Le Mercier et al. (2017) investigated the galling of Al6082-T6 aluminum alloy during cold forging process. Upsetting-sliding test (UST) was used for replicating metal-metal interface interactions, such as sliding velocity, contact pressure and temperature to evaluate the amount of deposited aluminum to tool surface. Schematic representation of the test set-up is illustrated in Figure 5 and the tested configuration is given in Table 4. Three trials were conducted for each test configuration in which a single tool and unworn aluminum sample surface was used. Cylindrical aluminum samples were lubricated with molybedenum disulphide. Combination of SEM and surface profilometry was used for surface analysis. This combined method was used and proved by Nosar [31] to be an efficient way of comprehending the mechanisms for controlling the transfer of materials. The main idea of this method came from the nature of topographical distinction between ground and polished surfaces. Surface topography image of the latter for steel tool consists of peaks with hard phase particles on nanoscale whereas grounded surfaces are characterized with macroscale scratches caused by abrasive particles such as SiC. Nosar [31] found that the optical surface profilometer alone was not adequate to define polished surface topography due to this difference and emphasized the importance of SEM addition to profilometer analysis for correctly identifying surfaces. Le Mercier performed this combined method to characterize topographies and make a quantitative analysis about galling. According to findings of the study, it was revealed that galling was observed in every test conditions and its regime was depend on the sliding velocity. At sliding velocities of 100 and 200 mm/s, the coefficient of linear regression was almost the same, indicating the same galling mechanism. At lower sliding velocities, such as 20 mm/s, a different linear regression coefficient was obtained, suggesting a different mechanism. Furthermore, a noteworthy relationship between wear volumes and the friction ratio has been emphasized which underscores the significance of considering a parameter that represents friction in adhesive wear models. The wear volumes exhibit similar trends as those noted in the friction ratio [17].

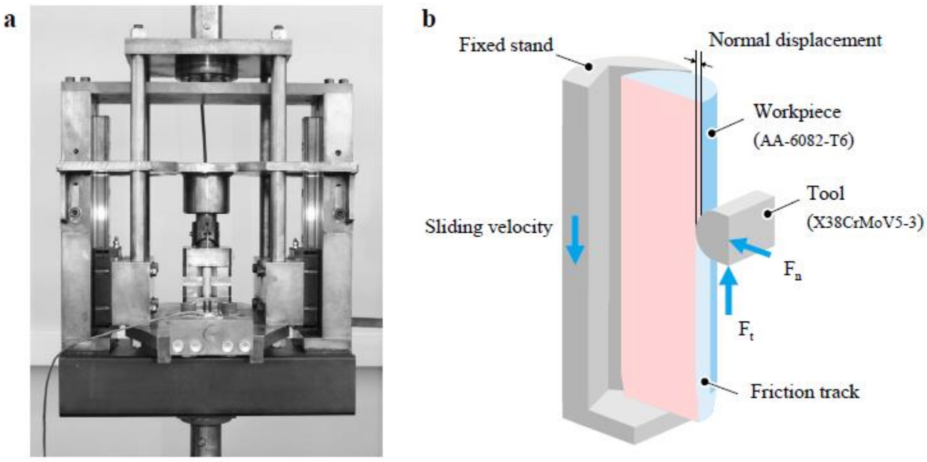

Figure 5. *(a) Upsetting sliding test device, (b) Schematic diagram of the test [17]*

Table 4. *Tested configurations [17]*

Tool/Test configuration	1	2	3	4	5	6	7	8	9	10
Sliding velocity *(mm.s^{-1})*	20	20	20	100	100	100	200	200	200	200
Normal displacement *(μm)*	30	60	100	30	60	100	30	40	60	100

Pujante (2013) conducted an experimental study on AA2017 aluminum balls with temperature ranging from 30-450℃ to examine the effect of temperature on wear behaviour. They used ball-on-disc sliding test with H13 tool steel where AA2017 ball was securely affixed within a holder connected to an oscillating electro-mechanical drive. This drive exerted pressure against a fixed tool steel disc, which was in turn positioned atop a heating block. The applied load was kept constant during each test and the coefficient of friction was measured. Tests were conducted for three set of tool samples with varying surface roughnesses and orientations. All experiments were conducted at 30℃, 150℃, 250℃, 350℃

and 450°C. Backscattered electron imaging and confocal microscopy were used to monitor groove depths and other wear induced formations for 10s and 300s duration which corresponded to 250 and 7500 sliding cycles respectively. In 250 cycle, groove depths were measured to be similar in all temperatures which was around 2-3µm. From 30-250°C tool abrasion was not observed and there were thin layer of aluminum alongside with lumps up to 30 µm due to metallurgical junction between metal-metal contact. But they were all removed later with repetitive sliding motion. However, at higher temperatures (350-450°C) tool abrasion was apparent. At those temperatures, deposited aluminum was converted into aluminum oxide and assisted abrasive wear mechanicsm on tool surface. In 7500 cycle, grooves were more deeper around 10µm without any material transfer, lumps of aluminum were detected but later abraded, for just above the room temperature. After 2500 cycle, coefficient of friction was stabilized. In between 150-250°C, material transfer was more pronounced and lumps that formed during the initial stages of the tests became a sites for nucleation growth and accelerated further material transfer. At the highest temperatures, 350-450°C, case groove depths were measured as 20µm which is the highest depth in all cases. Abrasion was so severe that it even removed material from tool steel. Authors didn't focus on the material loss from the tool but they reminded that H13 metal could operate around these temperatures without any disturbances caused by softening. So, this material loss could not be explained by thermal softening of the tool steel. In overall, conducted experiments demonstrated that temperature had significant effect on the wear behavior and it is an important parameter for forging process of aluminum. Authors also examined the effect of surface finish in some extend, but they concluded that its effect was negligible due to low surface roughness [32].

Pruncu et al. (2018) investigated the material transfer mechanism from Al6082 T6 alloy to tool steel under upsetting-sliding tests. The test set-up is shown in Figure 4. The tests were performed with various contactor penetration depths ranging from 0.04 to 0.18 mm and two different sliding velocities as 10 mm/s and 60 mm/s, respectively. Samples were separated into two groups, with one of the groups being lubricated with MoS_2 to prevent early damage. The results of lubricated and unlubricated samples were compared. Additionally, a new contactor was used for each test. The amount of transfered aluminum on contactor was assessed by measuring the initial and final thicknesses of the sample. In order to do that, maximum 10-point height method was used within the study. The results of the study revealed that, the amount of transferred material tended to increase with increasing plastic deformation. At high plastic deformation levels, the transferred material almost covered whole contact surface of the contactor. Even for low plastic deformation levels, aluminum adherence to contactor surface was observed. The transfer mechanism was explained as the initiation of aluminum adherence to the tool and the delamination of aluminum particles. As the deformation continued, the initial interactions between aluminum and the tool at the microscopic level gradually shifted towards interactions between aluminum to aluminum. The results of the study also highligted that, as the amount of transferred aluminum increased, the coefficient of friction was also increased. When the tests were performed with MoS_2 lubricant, the effect of transferred aluminum on coefficient of friction was low since metal to metal contact was minimized with the use of lubricant [33].

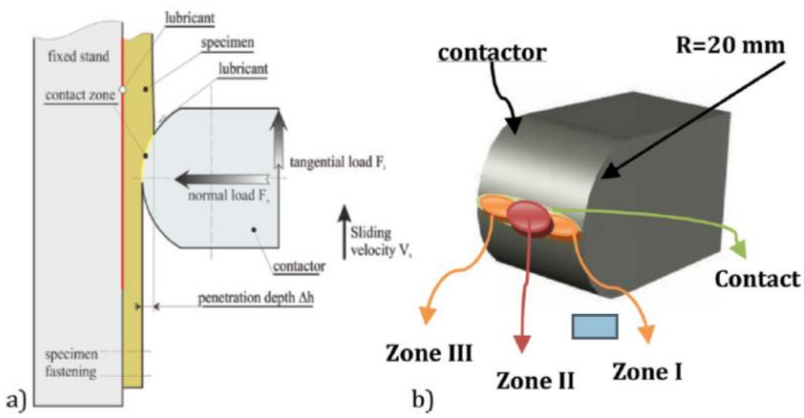

Figure 6. *(a) Schematic view of the upsetting-sliding test and (b) zones of analysis considered for the contactor surface [33]*

Vidales et al. (2023) studied the wear behavior of Al5754 with a focus on surface roughness and tool geometry. The authors also investigated the effect of coating and lubrication on the wear behavior. Experiments conducted in two parts: in the first part, effect of surface roughness and geometry of tools was studied while in the second part, performance of coating with various lubricants was examined. To analyze the effect of surface roughness, a modified version of scratch test was used in which aluminum ball was rubbed on the unworn surface of tools. Schematic diagram of scracth test is illlustrated in Figure 7 and test parameters are given in Table 5. The tool surfaces were prepared with different surface finishes as polished, machined and sand blasted. In order to investigate the wear and friction behavior of coated balls, ball-on-disc test with a tribometer was used. Tests were performed both with and without lubricants to reveal the effect of lubrication. The balls were manufactured with WC/Co and coated with two different bi-layered DLC coatings. The tests parameters and lubricant details are given in Table 6 and Table 7, respectively. Ball-on-disc tests with lubricants were carried out with the submerged system in lubricant. This was not an accurate simulation of the industrial operations. To simulate the real process and to verify the lab results, semi-industrial tests was also conducted. During these tests, two different punch geometries, straight or back-tapered were used. Additionally, within the study, used industrial punching tools provided by a company, was also investigated with field emission scanning electron microscopy (FE-SEM), energy dispersive X-ray (EDX) and infinite focus microscopy to reveal failure modes. These punching tools were used for the trimming of Al5754 parts. Through the surface investigation of industrial tools, the authors observed that the most visible damage was the galling on the side faces of the tools. The minimum aluminum adherence was observed with the polished tools, while highest adherence was observed with the machined tools. Although sand blasted tools had highest roughness within all tools, they showed less adherence than machined tools because of the anisotropy in surface roughness. Coating irregularities, such as micro-droplets, found to be adhesion provoker where thin aluminum layer was observed on polished tool with low friction coating. The results of the study also indicated that, the applied bi-layered DLC coatings showed similar behavior in terms of friction without lubrication during lab tests. When the lubricants were applied to the system, friction decreased regardless of the type of lubricant used. The best results in terms of galling was obtained with the use of back-tapered and polished punching tools coated with a-C:H/Cr DLC. In brief, tool surface roughness had an important effect on aluminum adhesion and with the combination of suitable tool geometry and coating, aluminum adherence could be reduced significantly [34].

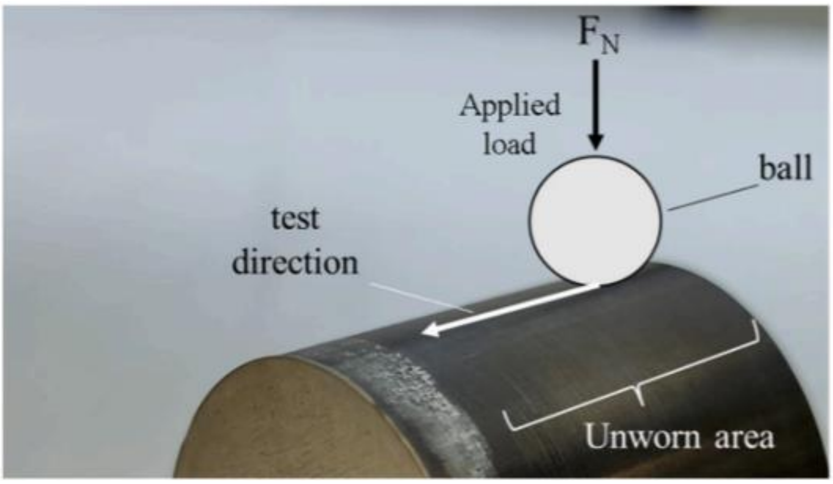

Figure 7. *Scratch test schematic diagram. [34]*

Table 5. *Experimental parameters of modified scratch test [34]*

Ball	Ø2.5 mm 99% Al
Load	1 N
Length	10 mm
Speed	20 mm/min

Table 6. *Friction test parameters [34]*

Spherical Indenter	Ø10 mm-coated WC/Co balls
Disc	Ø40 mm x 3 mm of aluminum 5754
Load	10N
Test environment	Dry & Lubricated
Total distance	85.5 m
Speed	95 mm/s

Table 7. *Lubricant characteristics [34]*

Lubricant	**Formulation**	**Viscosity** *(ISO 40°C)*	**Weld Load** *(kg)*
LUB 1	Mineral Oil + Ester additives	130 cSt	180
LUB 2	Mineral Oil + Ester additives	150 cSt	760
LUB 3	Ester Base + Additives	110 cSt	320

In literature, many experimental studies were performed to understand the effecting factors on aluminum adherence and friction conditions. However, there are a few studies related with the numerical approach to predict these phenomenon [35-37]. Given that cost of tools in metal forming processes can account for as much as 30% of the overall production cost [38] and considering that wear, galling, and friction conditions significantly shorten the lifespan of these tools, it becomes crucial to investigate numerical approaches for predictive purposes [39,40].

A simple example can be given for numerical investigation of maximum contact pressure on die-blank interfaces. Finite element modeling can be utilized to model contact pressure distribution over these parts and its response might yield to a favorable result to comprehend tool wear [41,42]. Similarly, coupling the friction models into finite element analysis is a favored method for evaluating friction [43,44] to increase die life in cold forming process. In this sense, there are several numerical studies related to galling of aluminum alloys. For instance, a methodology on predicting the galling onset was proposed by Filali for AA6082-T4 aluminum alloy in cold forming. Strip reduction test (STR) was utilized to investigate lubrication and onset occurence of galling, then, obtained results were compared with finite element results. Ductile failure and adhesive wear mechanisms were related to each other in order to predict galling. First adhesion of soft material to harder surface was taken as the beginning of galling and authors assumed that this material transfer was achieved for a critical damage value at the contact region. Since adhesion wear is related to friction at the surfaces, they suggested that the damage model used for such problem must include the effect of shear stresses. For instance, classical damage models such as Lemaitre's and Gurson-Tvergaard-Needleman (GTN) could only predict galling under extreme contact conditions where excessive tensile stresses are observed. Because these methods only consider tensile stress at the contact area and required critical damage values could be achieved only under such extreme contact conditions which is not appliable to common forming processes. Friction model was derived from work piece-tool contact and it was controlled by the lubricant. Wilson's lubrication model was implemented for normalized thin-film thickness, $\boldsymbol{z}$, to determine this contact conditions and modify the finite element model accordingly. Three seperate contact conditions were considered. If the contact was within a thick lubricant film, shearing of lubrication film was chosen as the main cause of friction stress and it was written as a function of lubrication viscosity. For thinner films, a shear stress factor was utilized to include the effect of surface roughness. In the thinnest case, two types of regimes were defined: mixed and boundary lubrication for direct and partial contact. Friction stresses were subsequently taken into account with parameters such as adhesion coefficient, fractional area of contact, contact pressures and strain rate. Comparison between purposed model and experiments showed general agreement with some deviations. Model had some errors in the sense of starting location of galling where it always predicted the location to be further than its experimental equivalent. Also, local adhesion of aluminum was found to be smaller than it was expected. Authors related these problems to mesh effect and Wilson model where it might overestimated ploughing friction stress. But in overall, their model was able to predict the onset of galling for both lubricated-unlubricated cases, and strip rupture due to traction [45].

II. CONCLUSION

The demand for aluminum and its alloys in the automotive industry is increasing day by day due to regulations aimed at reducing greenhouse gas emissions and improvements in electric vehicles. For both purposes, aluminum stands out as a lighter but durable material that can be used instead of steel. Despite its beneficial features, forming of aluminum at room temperatures is a challenging process due to complicated nature of the material. Aluminum has tendency of sticking to tools during cold forming processes that can decrease the overall quality of the manufactured part. Friction conditions and other forming parameters are crucial in order to delay the onset of the sticking. Many researchers have focused on the galling phenomenon that occurs during the forming of aluminum and its alloys and investigated the parameters that affect it. As a result of all the studies carried out, although galling cannot be completely prevented, critical and necessary conditions have been introduced to delay it. The effect of proper lubrication and coating is highlighted as a conclusion of studies. Also, DLC coatings gets attention of researchers and promise good results depending on the application. In addition to experimental studies, numerical studies are also presented to predict the galling onset before production and to reduce the trial and error.

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