Extremely smooth: how smooth surfaces enable dry and boundary lubricated forming of aluminum

Extrem glatt: Wie glatte Oberflächen eine trockene und grenzgeschmierte Umformung von Aluminium ermöglichen

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Abstract. Reducing the amount of lubricant down to dry frictional contact in aluminum forming still poses major challenges for research and industry. The (partially) dry frictional contact favors aluminum adhesion on the tools. Coating the tools with a:C-H (hydrogenated amorphous carbon) can lead to significant improvements, but recent findings show a surprising effect of both tool and sheet surface roughness and topography on the friction and wear behavior. This publication analyzes the friction and wear behavior of coated and uncoated tool and sheet surfaces for both dry and minimal lubricated applications. On the sheet side, the roughness of the sheet metal EN-AW 5083 is significantly reduced by polishing to R_z values in the range of 0.2 µm. Various phenomena are evident: Due to the reduced surface roughness, a by 50% improved coefficient of friction is achieved at low loads and plane-plane-contact even with smallest possible lubricant quantities. In the dry case, however, the surfaces show slight signs of wear. In the high load case both friction is significantly reduced to a coefficient of friction of 0.01 and no wear present on the tool surface both in the dry and minimally lubricated cases. The phenomena are attributed to the complex smoothing behavior of the surface topography and are analyzed based on surface parameters.

Keywords: Friction, Dry forming, Aluminum

Abstract. Die Reduzierung der Schmierstoffmenge bis hin zum trockenen Reibkontakt in der Aluminiumumformung stellt sowohl für Forschung als auch Industrie nach wie vor eine große Herausforderung dar. Der (teilweise) trockene

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Reibkontakt begünstigt Aluminiumadhäsionen an den Werkzeugen. Die Beschichtung der Werkzeuge mit a:C-H (amorphe Kohlenwasserstoffschichten) kann zu signifikanten Verbesserungen führen, aber neuere Erkenntnisse zeigen einen überraschenden Einfluss von Werkzeug- und Blechoberflächenrauheit und Topographie auf das Reibungs- und Verschleißverhalten. Dieses Paper analysiert das Reibungs- und Verschleißverhalten von beschichteten Werkzeug- und Blechoberflächen für trockene und minimal geschmierte Anwendungen. Auf der Blechseite wird die Rauheit des Blechs EN-AW 5083 durch Polieren auf R_z-Werte im Bereich von 0.2 µm deutlich reduziert. Dadurch sind verschiedene Phänomene zu beobachten: Durch die reduzierte Oberflächenrauheit wird bei geringen Belastungen und ebenem Kontakt auch bei kleinstmöglichen Schmierstoffmengen ein um 50% verbesserter Reibungskoeffizient erreicht. Im Falle trockener Reibung zeigen die Oberflächen jedoch leichte Verschleißerscheinungen. Im Fall höherer Lasten werden sowohl die Reibung als auch der Verschleiß deutlich auf einen Reibungskoeffizienten von 0.01 reduziert und es entsteht sowohl im trockenen als auch im minimal geschmierten Fall kein Verschleiß auf der Werkzeugoberfläche. Die Phänomene werden auf das komplexe Glättungsverhalten der Oberflächentopographie zurückgeführt und anhand von Oberflächenparametern analysiert.

Keywords: Reibung, Trockenumformung, Aluminium

1 Introduction

Aluminum is an excellent material for a wide range of applications especially in the automotive and aerospace industry due to its weight advantage and excellent energy absorption capacity. However, the high adhesion tendency of aluminum to numerous materials complicates the design and procedure of forming processes. To ensure a good component quality and stable processes a high amount of lubricants is currently required to prevent a formation of aluminum adhesions on the tool surface [1]. In case of dry forming processes, adhesions are rapidly formed on the tool surface leading to an immediate tool failure. For ecological sustainable dry forming processes of aluminum, effective strategies need to be developed considering the relevant wear mechanisms and influencing parameters.

One strategy is the deposition of hard thin film coatings to optimize the tribological properties of forming. Diamond like carbon (DLC) coatings and in case of this investigation the subclass of amorphous hydrogenated carbon (a-C:H) coatings are well known for their exceptional tribological properties [2]. Several investigations reported a low adhesion tendency in contact with aluminum [3]. Nevertheless, forming tools coated with state of the art a-C:H coatings still fail due to a rapid formation of aluminum adhesions comparable with uncoated forming tools [4]. Preliminary investigations identified the run-in behavior of a-C:H coatings as the reason for the rapid adhesion formation [4]. This behavior describes a short period at the beginning of a sliding contact, which is characterized by a high friction value and a distinct adhesion tendency. Meanwhile the a-C:H coating gets abraded leading to a nanoscopic smoother surface and improved tribological properties at the end of the run-in period. The interdependencies between the nanoscopic a-C:H surface roughness and the adhesion tendency were extensively investigated by Heinrichs [5]. Their tribological tests in laboratory scale indicated a high potential to prevent adhesion formation in dry forming processes of aluminum by using a-C:H coatings with nanoscopic exceptionally smooth surfaces. With regard to the sheet material, there are various investigations, which include the surface texture as an influencing variable. The dependence of the enclosed lubricant volume and the hydrodynamic pressure on the friction coefficient is investigated by Azushima et al. As the contact pressure rises, the real contact surface increases and leads to more lubricant trapped in the cavities reducing the frictional forces [6]. If the surface is relatively rough, a high contact pressure is necessary to achieve the friction-reducing effect [7]. Zhang et al. show that the friction-reducing effect is only possible if sufficient lubricant is available to fill the residual roughness in the tribological contact [8].

The aim of the test series shown in this paper is the tribological design of a dry or minimally lubricated deep-drawing process for aluminium. The various tribological load cases of deep drawing under dry and boundary lubricated conditions are investigated with regard to their friction behavior. The influence of the tool and sheet metal roughness will therefore be discussed. Both a:C-H coated and uncoated tools are used.

2 Materials and Methods

2.1 Strip-drawing test

The strip drawing test is a tribological test to characterize the friction and wear behavior in sheet metal forming. In this test, a sheet metal strip is loaded with a normal force by means of a hydraulic press over a tool pair consisting of an upper and a lower tool. A gripper then pulls the strip of sheet metal under load between the friction jaws. Various tool pairs are available for the test in order to simulate different load cases. Within the scope of this publication, both a cylinder-plane (CP) and a plane-plane (PP) tool configuration are used. The cylinder-plane configuration creates a line contact under high normal load on the sheet metal strip. This reflects the load case at the drawing die of a deep drawing process.

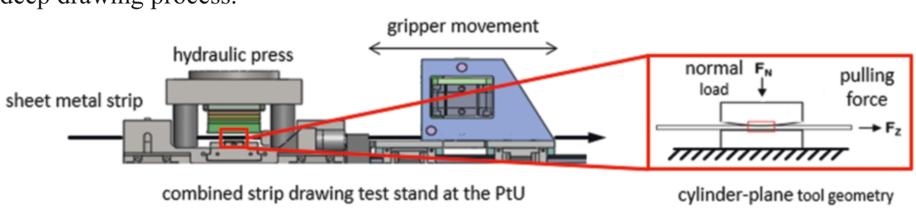

Fig. 1. Strip-drawing test at the PtU

The tribological conditions in the blank holder area can be approximated using the plane-plane configuration. Both tools have a footprint of 40 x 40 mm. The diameter of the cylinder defining the cylindrical surface of the tool is 258 mm. The normal force, drawing speed and sliding length can be precisely adjusted. These are selected in such a way as to correspond as closely as possible to the process conditions to be emulated. The test principle is shown in Figure 1 for the cylinder-plane geometry respectively. For each parameter set, three identical tests were carried out in order to be able to indicate the respective results and their scattering width. In order to ensure dry forming conditions, the sheet metal, the tools, and components in contact with the sheet metal prior to the blank holder were cleaned using acetone and isopropanol, which results in residual contamination layers below 100 nm, thus not influencing the tribological test [9].

2.2 Materials

The materials of the tools and the sheet material should also correspond as far as possible to those of the process to be simulated. In this case, the material EN AW-5083 is used. The surface finish of this alloy is a mill-finish surface, but it will be modified in this series of tests. The material belongs to the naturally hard alloys of the 5000 series and is characterized by magnesium as the main alloying element. The sheet material is cut to a width of 50 mm. The thickness of the sheet is 1.5 mm. For the test series with a reduced sheet surface roughness, the sheet strips were manually polished using a 1 µm diamond suspension ($R_z = 0.199 \pm 0.03$ µm). The original mill finish structure is removed. The mechanical properties are summarized in Table 1. The tool material is 1.2379 (ledeburitic Cr/Mo-Steel X153CrMoV12), hardened to 58 HRC, and manually polished resulting in a mean roughness depth of $R_z = 0.15 \pm 0.05$ µm.

Table 1. Material properties EN AW-5083

Material number (DIN EN 573)	Short symbol (DIN EN 573)	R_m [MPa]	$R_{p0.2}$ [MPa]	Material condition	surface finish
EN AW-5083	AlMg4,5Mn	>275	>125	O	mill-finish /polished

Some tools were coated with an a-C:H coating system, which was deposited by a plasma assisted chemical vapour deposition process (PACVD) with acetylene (C_2H_2) as the precursors gas combined with argon as process gas [10]. To enhance the coating adhesion, the substrates were sputtered clean for 30 min at the beginning of the coating process and an interlayer based on titanium with a thickness of 0.2 µm was applied by magnetron sputtering. The thickness of the complete a-C:H coating system measured 2.2 µm [11].

2.3 Experimental test procedure

The present investigations serve mainly for the tribological design of a dry or minimally lubricated deep drawing process. In the following, the coefficients of friction will be determined according to the test procedure in table 2 and 3. The lubricated tests were performed with the lubricant Wisura AK3080 ($\nu_{20°C} = 52$ mm²/s and $\rho_{20°C} = 0.9$ g/cm³) and the amount of lubricant did not exceed 0.4 g/m², which is a relative low value in aluminum forming operations. The lubricant was applied by a jet of high-pressurized air and the applied amount is verified gravimetrically, which limits the minimum amount of lubricant applicable. Due to the flat tools, the contact normal stresses can easily be calculated, as the normal force is adjustable.

It was not possible to evaluate the coefficient of friction of the tests both without lubricant and without coating, as adhesive wear on the tools occurred in all load ranges and the friction therefore cannot be compared with the lubricated or wear-free tests. It can therefore be assumed that a dry deep-drawing process is not easily possible for these pairings, since the high friction in the flange area leads to high drawing forces until the tensile stress exceeds the tensile strength of the material in the bottom of the cup and so-called bottom tears can occur.

Table 2. Test procedure plane-plane geometry (PP) for the blank holder area and the cylinder-plane (CP) geometry for the drawing die respectively, the drawing distance of 100 mm and drawing speed of 100 mm/s were kept constant during all experiments

	PP			**CP**
	5 MPa	**10 MPa**	**15 MPa**	**75 MPa**
Tool: uncoated, **sheet-metal:** MF				
· dry	Adhesive wear			x
· 0.4 g/m² AK3080	x	x	x	x
Tool: uncoated, **sheet-metal:** polished				
· dry	Adhesive wear			x
· 0.4 g/m² AK3080	x	x	x	x
Tool: a:C-H, **sheet-metal:** polished				
· dry	x	Abrasive wear		
· 0.4 g/m² AK3080	x	x	x	

a:C-H coatings show a relatively pronounced running-in behavior at dry friction, which is characterized by high wear and high friction. This can be avoided by first running the tools through several strokes in the lubricated case, so that the roughness on the coating can be removed. According to Abraham et al., a run-in length of 27m is particularly favorable for the coating used in this paper [11]. The contact normal stress of 75 MPa was derived by simulations and a validation by Fujifilm Prescale Measurement Film. Surface analyses were performed using a 3D confocal microscope µ-surf from Nanofocus with a LED light source. For the roughness analysis, a magnification of 100x was chosen. Characteristic areas were selected which represent the total surface quality of the tools.

3 Results and Discussion

Figure 2 shows the results of the test series for determining the coefficient of friction with the plane-plane geometry. In the lubricated case, the friction map shows the Coulomb coefficients of friction at different contact pressures. For the dry case, only one test was performed at a low load level. The error bars represent the coefficients of friction of three tests performed per set of parameters. The green curve corresponds to the reference case of an unpolished and uncoated tool against a mill-finish surface of the sheet metal with minimum quantity lubrication. For all contact pressures, the coefficient of friction is between 0.02 and 0.04 without a clear tendency with increasing contact pressure. An increasing contact pressure under optimal lubrication usually leads to a decrease in the coefficient of friction, as this favors hydrodynamic effects [6].

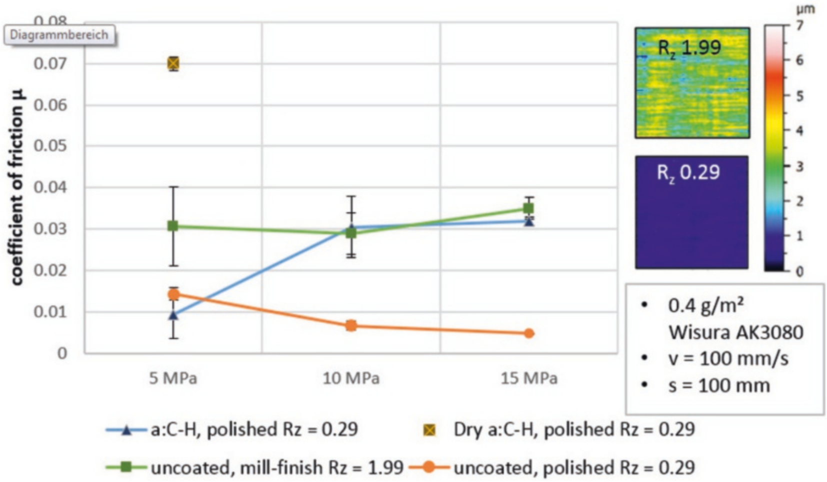

Fig. 2. Frictional analysis of the plane-plane contact according to Table 2

Independence from contact pressure can support the thesis of minimum quantity lubrication. The counterpart to the reference case is the orange curve. In this test, sheet material is used which has been manually polished in advance to reduce the sheet roughness from $R_z = 1.99$ to $R_z = 0.29$. It is found that the basic level of friction with smooth sheet metal is significantly lower than with the standard mill-finish surface. In addition, there is a clear tendency with increasing contact pressure towards lower coefficients of friction. The test series with smooth sheet metal were repeated with a:C-H coated tools, whereby dry friction tests without wear were also possible. For low surface pressures and a lubricated friction contact, the values for uncoated and coated tools are almost identically at 0.01. With increasing contact pressure of 10 MPa and higher, however, there is a strong increase in friction coefficients to values between 0.03 and 0.04. Microscopic analyses (Figure 3) show that although the basic roughness could be significantly reduced by the running in of the coating, there are clear scores on the surface of the tools, which indicate abrasive wear. This is probably due to small coating defects that prevent efficient running in and the associated reduction in roughness. In the further course of the experiments, this leads to a failure of the coating, particles from the coating can be carried by the friction contact, and cause abrasive wear marks. The anti-adhesiveness of the coating ensures that there are no aluminium adhesions on the surface after either the lubricated or the dry friction test. In the case of the dry test, however, in order to avoid further damage to the tools and to enable subsequent analysis, only three tests were carried out at 5 MPa contact normal stress.

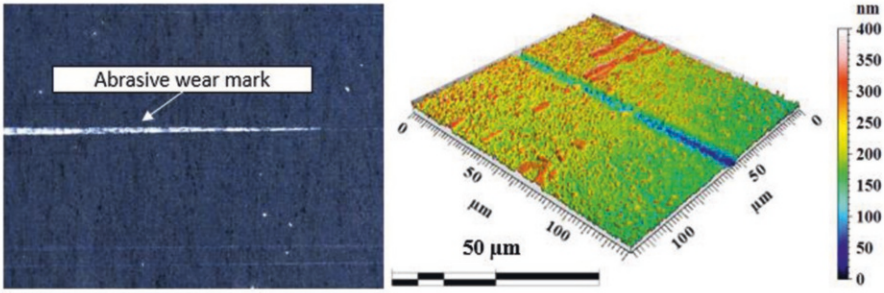

Fig. 3. Microscopic analysis of the a:C-H coating after running in showing an abrasive wear mark on the coating

The coefficient of friction of the dry test is also in a relatively low range of 0.07 with a very low error bar representing a stable frictional behavior.In summary, it can be said that a reduction in sheet roughness has a positive influence on the development of friction coefficients in the blank holder area.

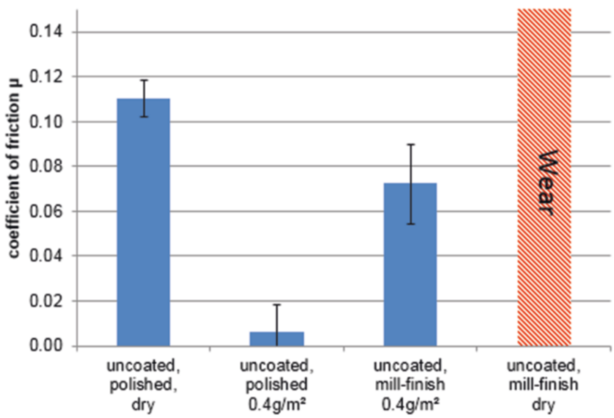

Fig. 4. Frictional analysis of the cylinder-plane contact according to Table 3

In the case of a lubricant quantity reduction up to the dry case, however, it can be seen that without a coating there is probably no process window in which an error-free deep drawing process seems possible. However, if run-in a:C-H coatings are used, the coefficient of friction may be low enough in the dry case to allow such a process window. Strip drawing tests with a cylinder-plane configuration were carried out, see Figure 4. The load conditions result in high contact normal stresses in the line contact, which correspond to the load on the drawing die of a deep-drawing tool. The friction behavior in this tool configuration differs in part significantly from that of the plane-plane configuration. While in the case of uncoated tools with the mill-finish surface no wear-free test was possible in the dry case, a very positive influence on the friction behavior of the sheet with reduced roughness is shown. Although the coefficient of friction is significantly higher than that of the plane-plane configuration, a wear-free test without tool coating is possible in this case with a friction coefficient around 0.11. The coefficient of friction for uncoated tools and mill-finish surfaces on the sheet material is between 0.06 and 0.08 in the case of minimum quantity lubrication, which means that by omitting the lubricant only a loss of 0.03 in the coefficient of friction can be expected. The coefficients of friction of the cylinder-plane configuration with smooth sheet metal and minimum quantity lubrication are in a very low range around 0.01, as is the case with the plane-plane tool configuration. Regarding the general friction coefficients and especially the difference between the mill-finished and the polished surface texture, it is also noteworthy that the friction coefficients are relatively low in the polished case compared to typical values in sheet metal forming. According to Czichos, the basic friction regime in the Stribeck diagram depends on the quotient of lubricant film thickness and average roughness values equaling λ, see equation 1 [12].

$$\lambda = \frac{\text{film thickness d}}{\sqrt{(R_{z_1})^2 + (R_{z_2})^2}} \tag{1}$$

With λ around one, boundary friction, meaning both friction partners are materially separated by a lubricating film in the area of the molecule size, is predominant. If one calculates the lubricant film thickness over a reference surface and the corresponding lubricant quantity, a thickness of 0.363 µm is obtained. The denominator with the roughness values from chapter 2.2 gives an average roughness value of 0.249 µm in the pairing with the polished sheet and 1.99 µm in the mill-finish case.

For this particular case the calculation of λ in dependence of the different roughness values gives $\lambda = 1.46$, where mixed friction would be predominant for the polished sheet and $\lambda = 0.16$, where solid friction prevails. In the case of the pairing of a polished sheet metal with a polished tool, a full separation and hydrodynamic effects might occur already at very low lubricant quantities.

4 Conclusions and Outlook

The friction coefficient analyses of dry or minimally lubricated deep drawing processes by means of strip drawing tests carried out in this paper showed that it is necessary to adapt the surface roughness of the sheet material to the tribological conditions. Although low coefficients of friction could also be achieved for the drawing die area using uncoated tools in combination with a smooth sheet metal, in the case of the blank holder area a tool coating using a:C-H coating is indispensable in order to be able to expect wear-free tests. Furthermore, it could be shown that a reduction of the lubricant quantity during the forming of aluminium also seems possible. In the following investigations, the friction coefficients generated are used to design a dry or minimally lubricated deep-drawing process. This will be done numerically and experimentally. The overall aim is to show by means of cup deep-drawing experiments, that it is possible to realize wear-free processes by influencing the coating and the sheet roughness.

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