

23rd International Conference on Material Forming (ESAFORM 2020)

The Effect of Material Surface Roughness in Aluminum Forming

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Abstract

In the last few years many efforts have been carried out in order to understand better what the real contact between material and tools is. Based on the better understanding new friction models have been developed which have allowed process designers to improve numerical results in terms of component viability and geometrical accuracy. Aluminum forming is especially critical since aluminum alloys have a higher tendency to generate galling in the tooling. In order to avoid galling problems, several strategies have been applied such as improving the surface quality of the tools, the application of special lubricants, the coating of the tooling surface or the generation of special textures in the tooling surface. However, not many researchers have focused in the effect of the surface texture of the sheet in the final tribological conditions at the interface. In the present paper 1050 aluminum alloy has been textured under different conditions in order to generate a wide variety of surface roughness. After that, strip drawing test have been carried out and the coefficient of friction depending on the contact pressure has been calculated. Finally, an industrial component has been simulated using the coefficient of friction calculated for the different surface roughnesses. This way, the impact of the material roughness in the component viability as well as in the component geometry has been evaluated.

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Peer-review under responsibility of the scientific committee of the 23rd International Conference on Material Forming.

Keywords: Aluminum; texturing; coefficient of friction.

1. Introduction

Today's manufacturing industry has to cope with increasing demands for lightweight design, especially in the transport industry [1]. Accordingly, an extensive use of lightweight materials, including aluminum, magnesium and titanium alloys is emerging [2]. Aluminum alloys provides several advantages including high strength to mass ratio and high corrosion resistance, and thus attracts large attention in engineering applications, such as automotive [3] and packaging. Sheet metal forming covers a broad range of processes, all designed to mechanically deform sheet material into a shape without material removal. Among them, deep-drawing [4] is one of the most commonly used forming processes in automotive and packaging applications, since allows a cost-effective mass production of components.

Tribological phenomena between tool and work piece can significantly influence metal forming processes [5]. Friction at the sheet metal-die interfaces affects the material flow in the manufacturing process, and wear of the tool surfaces could change the boundary conditions of the process, presenting a big influence on productivity and product quality. The forming of aluminum sheets presents a significant challenges due to the low formability compared to steel [6] and the material's vulnerability to undergo galling with the forming tools [7, 8].

In general, there is a consensus that the surface roughness of the frictional pair has an impact on the tribological properties of the system. It has been widely accepted that electro discharge texturing (EDT) improves the forming behaviour of aluminum sheets due to better friction behaviour [9]. Several research works demonstrated the improved performance of EDT surfaces against non-textured mill finish (MF) surfaces [10, 11, 12, 13, 14]. On the other hand,

although the patterned tool texturing has provided promising results [15, 16], it is widely accepted that the work material adhesion and galling risk increases with tool roughness [17] and appropriate polishing should be applied [18, 19]. Whilst galling is still not comprehensively understood, research efforts continue and there are some points that still need to be addressed. Although the interplay between the tool and the workpiece texture seems to be presumable, it has not been investigated. Previous research generally omitted tool surface roughness data [10, 12, 13, 14, 20]. Similarly, a broad range of roughness values are reported under EDT textured sheet definition, ranging from Ra 0.2-1,7 [10, 14], or quantitative data on the EDT texture was omitted [20].

The present work is built in this context, aiming at analyzing the effect that the sheet texture/roughness has in the forming of aluminum alloys. In order to do so, AA1050 aluminum alloys sheets have been textured under different conditions and strip drawing test have been carried out under different contact pressures. As a result the coefficient of friction curve depending on the contact pressure has been calculated for each of the surface roughness condition.

Finally a numerical analysis has been conducted in order to evaluate the impact that the change of the surface roughness, and therefore the coefficient of friction, has in the formability of aluminum components. A wheel-arch component has been selected and the effect of the surface roughness in its drawability as well as its final geometry has been evaluated.

2. Material mechanical properties

Commercial-grade aluminum EN AW 1050 alloy sheets have been used during the present research. The thickness of the material is 1 millimeter and its mechanical properties can be found in Table 1.

Table 1. Mechanical properties of AA1050.

Mechanical properties	
Yield stress (MPa)	127.29
Yield strength (MPa)	135.79
A (%)	3.49
r (0/45/90)	0.338/0.612/0.969

The reason for selecting this material is that the texturing device available at Mondragon University can not support high forces so a relatively soft material has been chosen for the initial experiments.

3. Texturing facility and roughness results

A texturing mill has been used at the present research. The device has two parallel rolls actuated by an electrical motor. The diameter of the rolls is 50 millimeters and they have been textured by EDT process. The roughness value of the texturing rolls (Sa according to ISO 25178-2:2012 standard) and measured with Sensofar S-NEOX optical profilometer using interferometry technique is 2.713 micrometers with an average deviation of 0.052. The texturing device is shown in Fig. 1

together with 3D images of the textured sheets obtained for each of the texturing conditions.

During the texturing of the material, sheets with dimensions of 300mm in length and 100mm in width have been used. Four different texturing levels have been generated and for each texturing level 50 specimens have been created. In order to achieve the different texturing levels, the distance between the upper and lower texturing roll has been modified. As a result, and based on the stiffness of the texturing device, different forces have been exerted during the texturing process and therefore different levels of texturing have been obtained. The texturing force has not been measured.

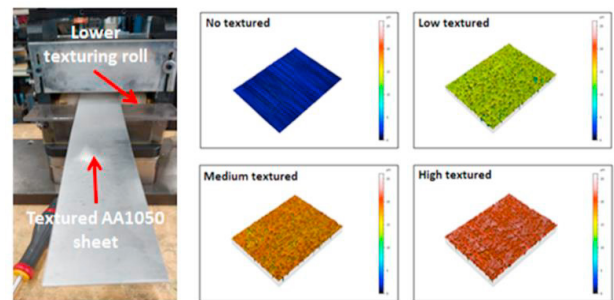


Fig. 1. Roll texturing device during the texturing of an specimen.

Due to the structural variability of the device, even if repetitions were carried out in the same conditions, the final roughness of the specimen varies. After some initial analysis of the capability of the texturing device, four different ranges of textured surfaces were generated.

Table 2. Roughness measurements obtained after the texturing of the specimens (measured by means of Mitutoyo SJ10 surfest profilometer under ISO 4287:1997 standard).

Texture range	Average roughness Ra (micrometers)	Standard deviation (micrometers)	Min roughness (micrometers)	Max roughness (micrometers)
No	0.14	0.02309	0.12	0.16
Low	0.9274	0.072	0.8	1.075
Medium	1.2298	0.066	1.1	1.35
High	1.7037	0.1445	1.47	1.98

For each of the specimens generated, eight roughness measurements were taken. Four measurement in each of the surfaces, upper and lower surface, two measurement areas, left and right size of the surface, and two measurement directions, longitudinal and transversal direction. Based on these measurements results in table 2, which describe the final surface quality achieved in the textured specimens have been obtained.

4. Friction results

The friction characterization was carried out using the Strip Drawing test [22, 23]. The tests were conducted using a biaxial testing machine of 4 independent 25t hydraulic cylinders. One of the cylinders made the clamping force while

the other cylinder pulled the sheet tangentially to the surface of the blocks, as set out in Fig.2.

The Strip Drawing tests were carried out at a constant velocity of 10mm/s. The tests were performed at different contact pressures ranging from 1 to 15MPa. The contact pressures that were evaluated were 1, 2, 5, 10 and 15MPa. This range was selected since the contact pressures when working with aluminum alloys in drawing operations are within it. For each of the contact pressures 3 repetitions were carried out.

The blocks used in the experiments were manufactured using a GGG70 tempered grey iron and the surface roughness was about 0.2 micrometers achieved through industrial hand polishing procedures. The hardness of the blocks' surface was 62HRc. The contact surface was 52mm in length and 26 mm in width. Fig.2 shows the blocks and one of the sheets during an experiment.

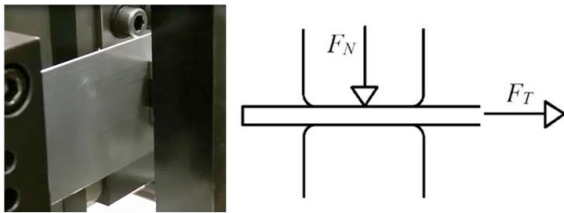


Fig. 2. Strip Drawing test at Mondragon University.

The procedure for the tests is as follows. For each test the surface of the aluminum sheet as well as the surface of the blocks was cleaned using acetone. After the cleaning of the surface, the surface of the aluminum specimen was lubricated using a manual application device. The lubrication was applied and after its application any remaining lubricant present over the peaks of the surface was cleaned. This way the valleys of the surface were filled with lubricant. The quantity of lubrication, based on 10 specimens lubricated in a row per texture condition, applied for each texture condition was measured using a gravimetric approach and the result is shown in next table.

Table 3. Quantity of lubrication applied for each texturing condition.

Texture range	Average quantity (gr/m ²)	Standard deviation (gr/m ²)	Min quantity (gr/m ²)	Max quantity (gr/m ²)
No texturing	1.74	0.2178	1.48	2.0
Low texturing	2.26	0.1890	2.0	2.4
Medium texturing	2.8	0.32	2.48	3.12
High texturing	2.9	0.4412	2.48	3.32

The lubricant used for the strip drawing test experiments was ALUBVS D05 metal forming lubricant. This lubricant is usually applied in industry when working with aluminum sheets and this is the reason for its selection. Its viscosity is 85 cSt at a temperature of 40 degrees Celsius.

The COF value was calculated from the relation between tangential force F_T and clamping force (two contact surfaces) F_N as presented in Equation 1.

$$\mu = \frac{F_T}{2F_N} \quad (1)$$

Based on the results achieved in the Strip Drawing test, a friction model was chosen to introduce the results in numerical modelling software. The model chosen to represent the tribological behavior of the materials was introduced by Filzek [24] as,

$$\mu = \mu_0 \left(\frac{p}{p_0} \right)^{n-1} \quad (2)$$

where m_0 and p_0 are reference values and n is an exponent defined within the range $0 < n < 1$. The coefficients for each texture condition have been calculated by means of the least square methodology using Microsoft Excel.

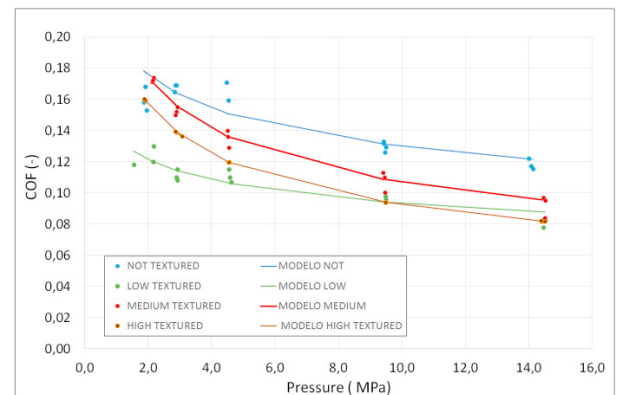


Fig. 3. Results obtained after the Strip Drawing tests.

The results obtained concerning the evolution of the coefficient of friction depending on the contact pressure for each of the textured conditions are shown in Fig. 3. Dots represents the different tests carried out for each of the texturing conditions meanwhile the lines represent the evolution of the coefficient of friction following the Filzek model.

It can be observed that the 'no texturing' condition, the material which has not been textured and that had an average roughness of 0.14 micrometers, shows the highest coefficient of friction. The other three surface conditions offer a lower coefficient of friction. The 'low texturing' condition, with an average roughness of 0.9274 micrometers offers the lowest coefficient of friction. This way it can be concluded that there exists a range of roughness close to one micrometer, where the coefficient of friction is the lowest, and that roughness above this value makes the coefficient of friction higher again.

5. Impact in a component forming

In order to evaluate the impact that the coefficient of friction has in the forming of aluminum components, an aluminum component has been selected and numerically analyzed using the friction conditions obtained with the four different texturing conditions. In order to get this, the coefficients of the Filzek friction model (see Equation 2) have been calculated for each texturing condition and introduced in

the modelling software, in this case Autoform R7.2. The coefficients are given in Table 4.

Table 4. Coefficient of the Filzek friction model for each of the texturing conditions.

Texture range	μ_0	p_0	n
No texturing	0.2050	0.8832	0.8121
Low texturing	0.1414	0.8166	0.8333
Medium texturing	0.2122	1.055	0.6938
High texturing	0.2017	0.9288	0.6710

The component selected is a wheel-arch manufactured using an aluminum alloy AA5754. The aluminum alloy AA1050 is used for the texturing but its low hardening behavior does not make it suitable for the drawing of this component. That is why the real material is used for the manufacturing of the component. The results shown next are based on the mechanical properties of AA5754 aluminum alloy and the frictional parameters used are the ones obtained in the Strip Drawing test made with the AA1050 alloy.

Two different aspects have been analyzed. On the one hand the impact of the surface texturing in the drawability of the component has been evaluated. In order to achieve this, the deformations obtained in the component have been evaluated after the main forming of the component usually carried out in the first step of the process. After this, and due to the fact that the frictional behavior has also an impact in the stresses introduced in the component and therefore in its final springback, a geometrical comparison of the final components after all the forming steps has also been carried out. It must be taken into account that the galling phenomena, observed during the strip drawing test, have not been considered during this numerical analysis.

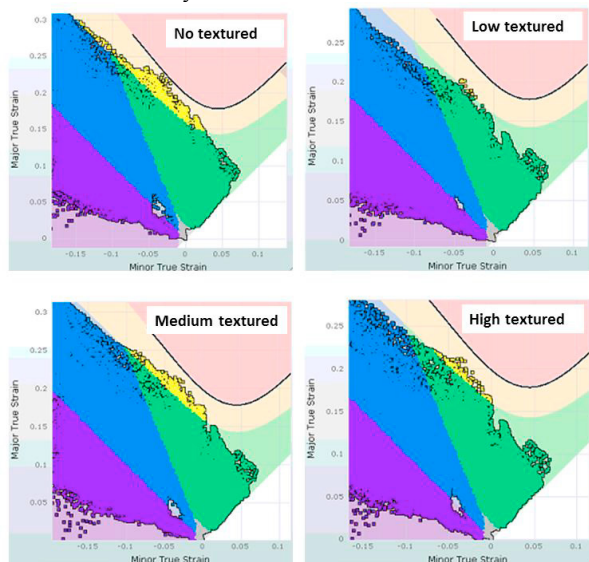


Fig. 4. Formability results for the component under the four different texturing conditions

Fig.4 shows the comparison carried out in terms of component drawability after the first drawing operation. It can be observed that when using the 'no texturing' condition, average roughness of 0.14, there are several areas in the component very close to breakage (yellow area in the FLD) and therefore the first drawing operation would give as a result components very close to failure. On the other hand, when using the 'low texturing' condition, it can be observed that the safety margin of the first drawing operation is much higher and there is almost no area in the component in a risky situation. 'Medium texturing' and 'high texturing' conditions offer intermediate results with the 'medium texturing' condition being the more risky situation.

Besides the drawability of the first operation, a geometrical comparison of the final component depending on its surface texture condition has been carried out. The purpose is to prove that the texture of the material has also an influence in the final geometry of the component.

Fig. 5 shows the results achieved in the comparison. The three images show the geometrical deviation of 'low texturing' condition, 'medium texturing' condition and 'high texturing' condition compared to the initial condition of the material, the 'no texturing' condition. There exist geometrical deviation up to 1.5mm in one direction (positive values in the scale) and 1.2mm in the other direction (negative values in the scale). This means that the total deviations are almost as high as 3mm. This would result in components being out of tolerances even if they do not break during the forming process. So this result proves the importance of the surface texture in the final geometry of the components.

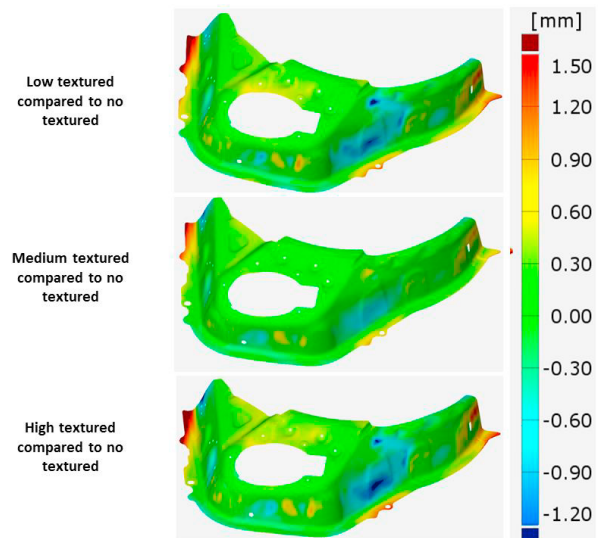


Fig. 5. Geometrical variations of the final component depending on the surface texture condition

6. Conclusions

The results show the importance of the surface roughness of aluminum alloys in terms of forming technology. First of all, the roughness of the material surface has a direct impact in the coefficient of friction in the process. A sheet surface

roughness of about 1 micrometer (0.9274 ± 0.072 at the present work) offers the lowest coefficient of friction when working with forming tools with a surface roughness of 0.2 micrometers and under these drawing conditions.

Besides the effect measured in the coefficient of friction, the paper also analyzes the effect of the surface texturing in the drawability of the material and the impact in the final geometry of the components (analysis based on a wheel-arch component). The surface texture has a direct impact on the drawability of the component. In this case a 'low texturing' condition offers the highest safety in the component drawing operation.

Furthermore, the impact of the roughness in the final geometry of the component has also been analyzed. Deviations of up to 2.7 millimeters have been observed depending on the surface roughness.

Acknowledgements

The authors would like to thank Spanish Government for the funding of the project ALUTOOL: Desarrollo de nuevas tecnologías de vanguardia para la producción de superficies funcionales de alto valor añadido orientadas al sector del estampado de aluminio under the program RETOS with reference number RTC-2017-6245-4 and financed by Ministry of Science, Innovation and Universities. The economical support, collaboration and technical support in the study of the company BATZ S. Coop. is gratefully acknowledged too.

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