Analysis of Work Hardening and Tribological Changes After a Gap Controlled Drawbead Passage

Harald Schmid and Marion Merklein

Abstract In deep drawing processes, drawbeads are frequently used to control the material flow while forming. It is well known that material parameters are changed significantly after a drawbead passage. Also, there are many references that the tribological system after a drawbead is changed and that this has influences on the ongoing forming process. In this study, the connection between work hardening and the tribological system after a drawbead is analyzed with respect to the initial state. Therefore, sheets are drawn through a gap controlled drawbead passage while parameters like the gap between blank holder and die or the materials are varied. Afterwards, hardness measurements will be carried out as well as 3D surface measurements to correlate them. For these investigations, three different sheet metals are used: a conventional deep drawing steel, an advanced high strength steel AHSS, and an aluminum alloy, as they represent the variety of industrial used sheet metal.

Keywords Deep drawing · Drawbead · Work hardening · Surface modification · Friction

1 Introduction

Functional integration of modern deep drawing parts, for example, in the automotive industry, leads to complex design in modern forming processes [1]. As consequence, forming operations of sheet metal face demanding geometries. Failure and defects are possible as well as unwanted thinning. Therefore, material flow control in a deep drawing process is important. In literature [2], different types of material flow control are described: Firstly, the adjustment of the blank holder force to control the flow

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in the flange area. In addition, the sheet metal layout can be changed and double-checked in simulations. Also, a change of the lubrication system, most of the times by changing the oil type or the oil amount is possible. For higher retention forces, drawbeads are used usually. Drawbeads do not only affect the material flow, but also have impact on mechanical properties [3] and tribological characteristics [4]. On the mechanical sector, work hardening and the significance of the Bauschinger effect was investigated and proven before [5]. Also the failure behavior is changed, according to Ke et al. [6], what was examined in tensile tests with material preloaded in a drawbead. This was also investigated by the authors in [7], and it was demonstrated that important material parameters are changed significantly. Next to that, there are also indications for tribological changes. For example, Staeves [8] showed an effect by drawbeads on the topography and Green [9] demonstrates that every contact of the drawbead has influences on the material itself. Trzepiecinski and Lemu [10] are analyzing a 5xxx-series of Aluminum and parameters like the rolling direction (R.D.) or the lubrication. Trzepieciński et al. [11] show various topographies of material in the initial state and after a drawbead passage and also differences compared to the bounder area. In addition, significant differences in the smoothening can be seen by the preloading direction. Azushima et al. [12] analyze the behavior of aluminum in bending tests and investigate a combination of roughening and smoothing effects. [13], a roughening effect on the outside of free bending is observed. According to the authors, smoothing takes place especially under high loads, and the differences on the surface of both sides of the sheet are also described. In [14], a change of friction coefficients after a drawbead is proven. By the authors, it was shown in [15] that an effect of the drawbead is evident for S_a and V_{cl} and it needs to be distinguished between the in- and outside of the sheet metal after a drawbead passage. The abrasive behavior of aluminum and the oil distribution after the drawbead is discussed. It is determined that steel materials are smoothened significantly while aluminum is roughened on the outside. Also, the coefficient of friction is influenced by pre-stretching in the forming area. To summarize this, a change of the mechanical and the tribological system is stated in many scientific publications. Until now, there is no cause-dependent correlation and therefore no physical explanations of these effects. Therefore, strip drawing tests with drawbead geometry are analyzed on the mechanical and tribological side. As a result, retention forces are evaluated as well as the surface topography on the in- and outside as a characteristic value for the tribological behavior. Variation is done for the tool distance of the drawbead and the material itself. Hardness measurements are performed for one tool distance variation. Analysis and discussion is done to find or determine if there is any direct connection between the parameters and the effect variables that can influence the tribological behavior.

2 Materials and Experimental Setup

In this chapter, the used materials and the experimental setup as well as the applied methodology are named. One material investigated is the aluminum alloy EN AW AA6014-T4 according to EN 573-1:2005-02, which was aged to a stable condition for six months. These sheets are mostly used in body shell or structural components as a lightweight material because of the low density and high strength compared to other materials. Also a deep drawing steel CR 3 GI 50/50-U [16] with 50 g/m^2 of hot-dip zinc coating is analyzed and will be called DC04. In addition, the material AHSS CR 440Y780T-DP GI40/40 [16] as a representative for a high strength steel is analyzed and will be called DP800. All sheet metals are delivered in the initial thickness $t_0 = 1.0$ mm. In Table 1, the material parameters derived, from uniaxial tensile tests A_{50} and from results of confocal microscopy, are presented.

As expected, DP800 has the highest yield strength YS and tensile strength TS. In comparison, the uniform elongation ε_u of DP800 is smaller compared to AA6014 and DC04. The confocal microscopy was used to describe the surface topography of the applied materials. Therefore, similar to the methodology in [15], the parameter S_a of the analyzed area as the mean arithmetic height is chosen to quantify the surface globally. S_a as the arithmetic mean height is able to describe the overall roughness and is, for example, also applied in commercial tribological software like TriboForm [17]. It can be seen that the surface of aluminum before forming is smoother compared to the steel. With these initial values, different behavior in mechanical and tribological changes can be expected. The drawbead geometry and the tool are shown in Fig. 1.

The nominal thickness of the material is $t_0 = 1.0$ mm; in reality, the materials AA6014 and DC04 are slightly thicker (~1.02 mm) while DP800 is a little bit thinner (0.96 mm). As mentioned before, strip drawing tests with drawbead geometry and a constant tool distance d between die and blank holder are used in the setup. The drawbead chosen has a height of h = 5.0 mm. The tool distance d is varied between 1.05, 1.10 and 1.15 mm as these are common values. The gap is defined by an adaptive system with two rails to fulfill an exact distance when closing with forces up to 100 kN. The gap to be set is double-checked with gauge-blocks and repeatable adjusted with a tolerance of +0.01 mm. All drawbead tests are performed with a drawing velocity of v = 50 mm/s and a lubrication of 2.0 g/m^2 KTL N 16, the oil amount was controlled with an optical system INFRALYTIC NG 2 (Infralytic GmbH), that was

Table 1 Material and topography parameters for AA6014, DC04 and DP800 in initial thickness of $t_0 = 1.0$ mm from uniaxial tensile tests A_{50} and confocal microscopy by Nanofocus µsurf

	Tensile strength TS [MPa]	Uniform elongation ε_u [%]	Mean arithmetical height S_a [µm]
AA6014	249.6 ± 1.7	20.0 ± 0.2	0.72 ± 0.01
DC04	303.7 ± 0.3	25.7 ± 0.6	1.31 ± 0.03
DP800	808.2 ± 3.4	12.9 ± 0.3	1.28 ± 0.02

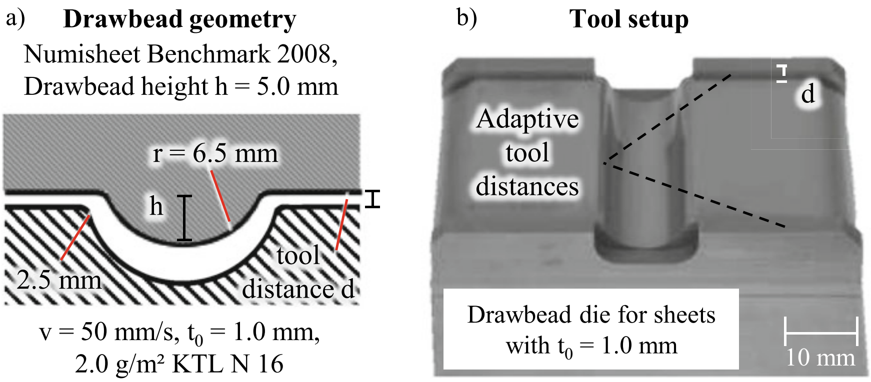

Fig. 1 **a** Details of drawbead geometry and **b** drawbead die with applied tool distancing. (Color figure online)

calibrated before. For every variation, n = 5 repetitions are drawn through the drawbead. Before and after the drawbead preloading, Brinell hardness measurements are performed. In pretesting, it was found that Vickers measurements are not suitable as the imprint was not evaluable after preloading due to the springback and deformation of the strips. So, Brinell hardness with circular imprints is determined by using the so-called Testor (Instron-Wolpert GmbH) with a loading of HBW 2.5/62.5 according to DIN EN ISO 6506-1:2014 with a ball diameter of 2.5 mm and a measuring force of 62.5 kP corresponding to 612.9 N. This evaluation is used to determine the surface hardness and was found to work suitable on the in- and outside and differentiate the hardening. The hardness is measured on every specimen on the in- and outside. Due to the deformed specimen after a drawbead, the sheet metal was clamped. In Fig. 2, the Brinell hardness measurements and the 3D-surface measurement by using Nanofocus µsurf are shown.

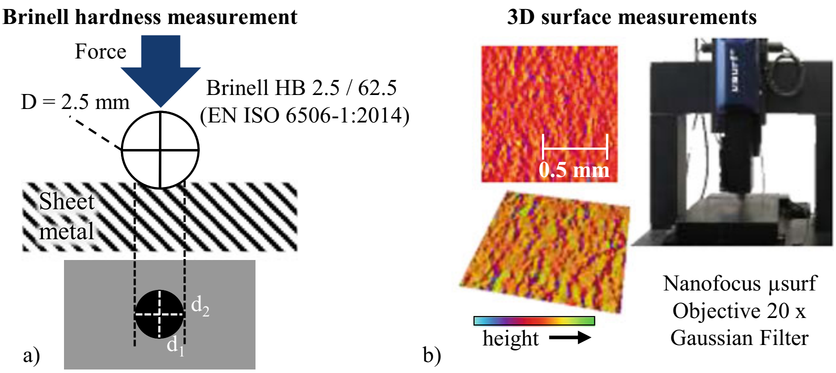

Fig. 2 **a** Process of hardness measurements Brinell HBW2.5/62.5 and **b** process for confocal microcopy of sheet metal after a drawbead preloading. (Color figure online)

For the confocal measurements, an objective with 20× magnification and a measuring size larger than 2 × 2 mm^2 was used and a Gaussian filter is applied. Every specimen was measured on the in- and outside after a drawbead passage for three times: left side, middle, right side. This is to guarantee repeatable values and to prevent any deviations between right and left sides. This means, every single specimen was measured by confocal microscopy six times, one variation is measured 30 times in total. In the following chapter, the results of the different measurements are presented.

3 Results of Drawbead Preloading

In this chapter, the results of the mentioned experimental setups are shown: the specific retention forces for different drawbead and material variations, confocal microscopy results and the corresponding Brinell hardness measurements.

3.1 Strip Drawing Tests and Retention Forces

In Fig. 3, the specific retention force, defined as the retention force related to the strip width, is shown as subject to the material and the applied tool distance d. The standard deviations are varying about maximum of 3.5% around the average and are therefore reasonable. A first observation is that AA6014 has specific retention forces up to 100 N/mm, DC04 up top 150 N/mm and DP800 up to nearly 300 N/mm. This is also due to the varying material strength as can be seen in Table 1. It is also obvious that the specific retention force is maximum for a tool distance of 1.05 mm. The rise of the retention force is between 5 and 7.5% for a step of 0.05 mm in the tool distance. The highest changes can be seen for AA6014, as also having the lowest

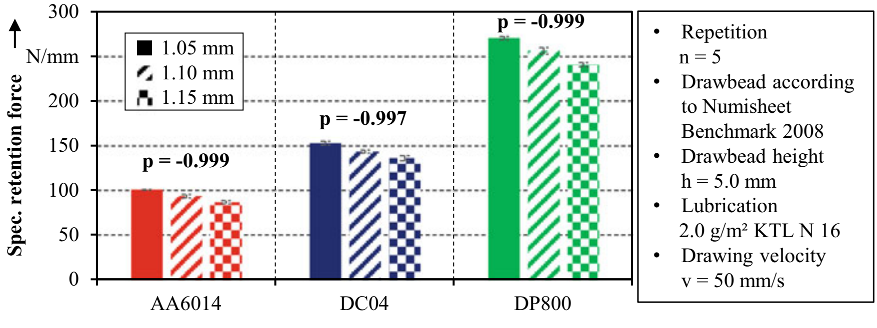

Fig. 3 Specific retention forces for AA6014, DC04 and DP800 when varying the tool distance d between 1.05, 1.10 and 1.15 mm. (Color figure online)

yield strength YS. When correlating the tool distances with the specific retention forces, Pearson's correlation coefficient can be evaluated to $p_{AA,DP} = -0.999$ for AA6014 and DP800 and $p_{DC} = -0.997$ for DC04. This means a nearly perfect negative linear relationship between the tool distance and the specific retention force. This relationship is expected to be valid in a defined range of d, as the geometrical conditions might change otherwise.

With the tool, various tool distances d can be realized by changing the rails. The tool distance d was set to match all materials. After the investigation of the retention forces as a specific value for the drawbead, the surface topography will now be considered.

3.2 Confocal Microscopy After a Drawbead Passage

Figure 4 shows the results for the arithmetic mean height S_a by confocal microscopy that was explained in chapter "A Vision of Numerically Controlled, Autonomous Manufacturing and Metal Forming". All of the different variations of Fig. 4 were tested on the in- and outside as well as the initial state.

Each bar represents the average of five specimen with each three measurements on the in- and outside. First of all, the initial arithmetic mean height S_a is lowest for AA6014 with 0.8 µm followed by DP800 with 1.2 µm and DC04 with about 1.3 µm. This could be also a result of the zinc coating on the steel materials. For AA6014, changes can be seen after a drawbead passage compared to the initial state, which was already stated in [14, 15]. On the outside, a roughening is apparent after the drawbead, which becomes more noticeable with higher tool distancing to a rise of nearly 20%

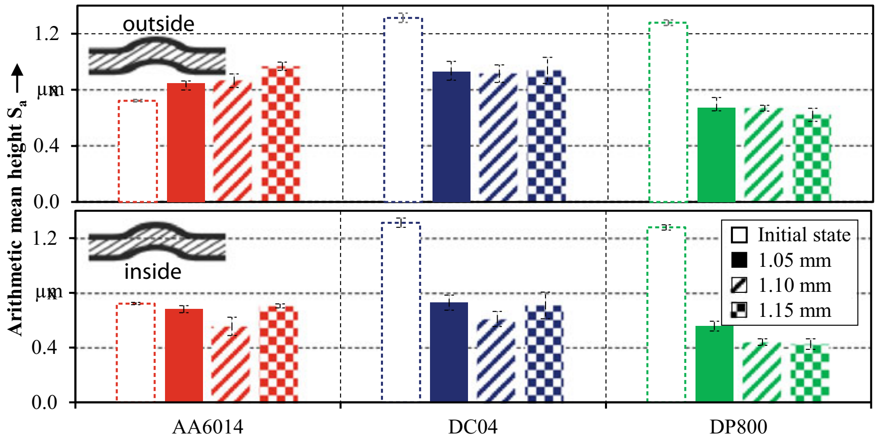

Fig. 4 Arithmetic mean height S_a for the initial state and after a drawbead passage for different variations of the tool distance d, the materials and the in- and outside for n = 5 specimen for each variation. (Color figure online)

at 1.15 mm. On the inside of AA6014, a smoothening is visible and S_a is reduced about 30%. Interestingly, smoothing is not maximum for the smallest tool distance. This could indicate different stress states according to the changed geometry. For DC04, the changes for S_a are even higher. The smoothing on the outside leads to a value of $S_a = 0.9\ \mu m$ and results in a reduction of 30% which is constant in between the standard deviation. The arithmetic mean height on the inside of DC04 is reduced between 44 and 53%. Also here, the reduction is maximum for the tool distance of d = 1.10 mm what was also seen for the inside of DC04. The material DP800 shows the highest reduction of S_a in general. The inside value is reduced up to 40%, the outside even to 64%. For the smoothing behavior, higher S_a values for smaller tool distances are the outcome. Regarding retention forces, expectation would have been also the other way round. In general it can be stated, that surface parameters after a drawbead passage are not clearly predictable by the geometrical value tool distance but a smoothing is expected for steel materials.

3.3 Hardness Measurements After Drawbead Preloading

For a better understanding of the work hardening effects on the sheet metal surface, Brinell hardness measurements were done on the in- and outside. Brinell's hardness was chosen to measure directly on the surface. This is also due to spring back effects when evaluating the imprint optically. The specimen were clamped on a metal plate. To measure the inside of the specimen, a formed tool with a smaller radius than the strip was used to ensure the planar measurement without any suspensions. In Fig. 5, the results for the Brinell hardness measurements are shown.

First of all, the initial hardness of the three materials varies: the hardness of AA6014 values is located around 60 HB in the beginning while DC04 locates around

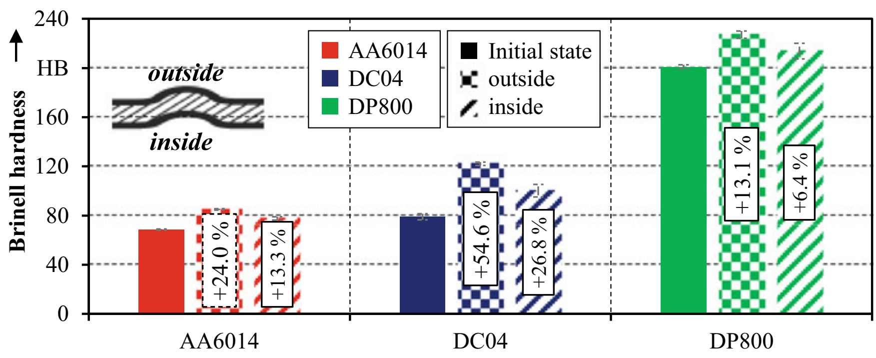

Fig. 5 Brinell hardness measurements for AA6014, DC04 and DP800 before and after a drawbead passage at d = 1.10 mm and grouped by in- and outside with n = 3 specimen measured. (Color figure online)

80 HB, DP800 has more than the doubled initial hardness with nearly 200 HB before the forming process. After the geometrically identical drawbead passage, a rise of the hardness between 6% up to 55% can be observed. In addition, on the outside the hardness is higher, what was also investigated for a another drawbead geometry by microhardness measurements in [3]. For AA6014 a rise of 24.0% on the outside and of 13.3% on the inside are visible. The final hardness locates around 80 HB. The initial hardness of DC04 is also located at 80 HB, the outside is hardened to 120 HB and the inside to 100 HB. For the deep drawing material DC04, the work hardening effects are the highest compared to the others. DP800 rises its hardness between 6 and 13%. In the following chapter, results will be correlated and discussed by giving possible explanations.

4 Discussion

First of all, a correlation between the specific retention force and the surface parameter S_a as a characteristic value for the tribological changes is discussed. Therefore, in Fig. 6, the forces and the surface parameters on the in- and outside after a drawbead preloading are shown normalized.

The retention forces were normalized to the value of the variation d = 1.15 mm, and the surface values were normalized to its initial state. The retention forces follow a linear correlation with the tool distance d, what could be possible due to a linear rise of friction and bending forces in this range of d what was also shown in Fig. 3. On the other hand, the surface parameter S_a does not behave the same way. Depending on the material, the smoothing on the inside is most significant for d = 1.10 mm and the inside is smoothened higher compared to the outside. DP800 has the highest retention forces but also has the lowest values for S_a compared to its initial state. Considering the materials only, a negative correlation between the smoothing and the forces can be drawn. Higher retention forces for each material are followed by more

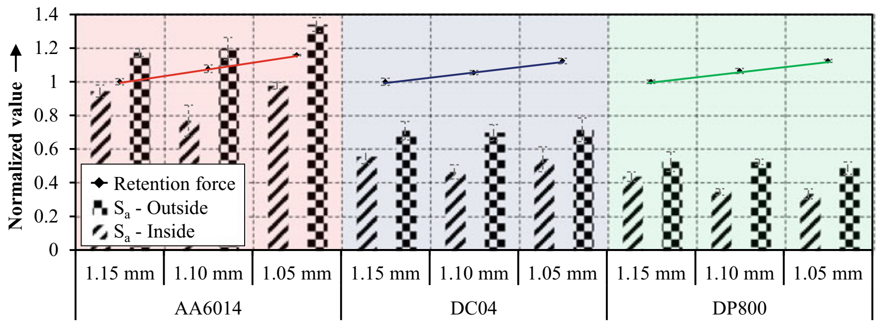

Fig. 6 Retention forces correlated and normalized with the arithmetic mean height S_a on the inside and outside. (Color figure online)

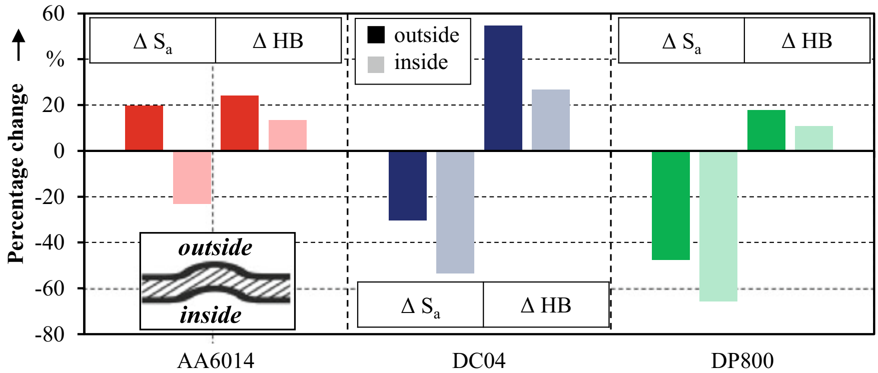

Fig. 7 Percentage change of the arithmetic mean height S_a and the Brinell hardness HB for the tool distance variation of d = 1.10 mm and the materials AA6014, D0C4 and DP800. (Color figure online)

significant smoothing, what could also be said in connection to the yield strength YS. After considering the surface and the retention forces for all the variations, a connection between the Brinell hardness results for the tool distance d = 1.10 mm and the surface parameter S_a will be drawn. Therefore, the percentage change of both values compared to the initial material value is shown in Fig. 7.

For all materials, except for the outside of AA6014, a smoothing simultaneously with a hardness increase is certifiable. The smoothing is also higher on the inside while the rise of hardness is higher on the outside. For aluminum, a statement is hard to make. The outside of AA6014 is the only area to roughen in a drawbead passage while the hardness is increased. In general, for AA6014, the arithmetic mean height S_a and the hardness are changed with a maximum of about 20–30%. The roughening effect for AA6014 compared to the steel seems to be interesting for further investigations. For DC04, the percentage change is located between 50 and 60% considering maximum values. In opposite, the material DP800 has only a rise lower than 20% looking at the hardness but a reduction of S_a of over 60% for the inside. That means, the material with the smallest rise in hardness has the highest reduction in its surface parameter S_a. Correlating these results to DC04, the changes seem to be more balanced there. A geometrical explanation of the correlation of hardness and smoothing behavior can not be drawn directly. Here, different approaches for an explanation are possible: The contact on the inside in a drawbead passage seems to provoke a higher smoothing effect for every material. Otherwise, on the outside the hardness is increased higher compared to the inside after a drawbead passage. An idea could be that the contact conditions are playing a key role for the behavior. A longer contact area with lower values on the inside could lead to higher smoothing effects while higher contact pressure located in a smaller area follow in a more significant increase of hardness. This would also be dependent on the geometrical circumstances of the alternating bending the location of contact areas. Also, the used aluminum and steel materials having different coating and therefore most possible different friction and smoothing behavior. Next to the contact pressure, the effect of topography changes due to tension, compression, or bending effects needs to be considered. According to Wechsuwanmanee et al. [18], the surface roughness plays an important role on the bending behavior and a difference to an ideal smooth surface is existent. For example, Muhamad et al. [13] show the increase of roughness during a wrap-bending process on the outside for a extruded aluminum and analyze material related reasons. For an integrated understanding of the topography changes in a drawbead, the combination of alternating bending processes with overlying tension needs to be investigated in detail step by step, also differentiating between the in- and outside. As an example, in investigations from Jonasson et al. [19] a direct correlation between the friction coefficient and common surface parameters was not found and can also not expected. As only the tool distance d is varied in a range of $\Delta d = 0.1$ mm, the variation of surface parameters in between one material is expected to be most likely a reason top different contact pressure effects. Also the yield strength YS and the hardening coefficient n could also influence the hardness behavior, which was also described in [7]. While YS and the work hardening coefficient n are quite similar for AA6014 and DC04, these two values are differing significantly for DP800. The influence of an oil reduction after a drawbead passage was also varying [15]. It seems that the oil reduction is high on the outside, where also the highest hardness increase takes place. This could also indicate a connection between the applied contact pressure, the oil reduction, and the final hardness. Unfortunately, this effect is very difficult to investigate in an experimental setup in a drawbead geometry although experimental setups like Filzek's [20] with respect to the Hertzian stress seem as a good start for further investigations.

5 Summary and Outlook

In this publication, the specific retention force, the surface parameter S_a as a value representing the tribological condition of sheet metal and the Brinell hardness were investigated before and after a drawbead passage and correlated. Therefore, the Numisheet Benchmark 2008 drawbead geometry was used with a drawbead height of $h = 5.0$ mm and tool distancing d was varied in three steps from 1.05 to 1.15 mm for the materials AA6014, DC04, and DP800. The most distinctive findings are

- There is a clear linear correlation evidenced by Pearson with $p = -0.99$ between the specific retention forces and the tool distance d for all investigated materials. This is expected to be valid in a specific range only.
- A correlation between the tool distance d and the surface parameter S_a could not be drawn clearly.
- Smoothing is visible for all materials and preloaded surfaces except for the outside of AA6014. This could be explained by the aluminum oxide layer and its special

reaction to alternating bending with overlying tensions. Next to the contact pressure variation, the influence of alternating bending and tensions on the surface roughness needs to be mentioned.

- Smoothing effects are more significant on the inside than on the outside after a drawbead passage. The reduction of the arithmetic mean height are up to - 60% for DP800.
- Hardness is increased on the in- but more significantly on the outside of sheet metal after a drawbead. While the outside hardness increased, the smoothing effect is more significant on the inside. An interesting observation is that low hardness changes are corresponding with high reductions of S_a for DP800. This could be due to higher contact pressure in combination with a higher yield strength of DP800.
- A significant influence on the tribological behavior is expected for every material deriving from the changes in hardness and surface values. Regarding the value S_a, the highest change is expected for DP800. Also considering the surface hardness, a tribological transition is probable for the mild steel DC04, too. After the results for the same blank holder force in [15], an integrated approach of the mechanical and tribological behavior taking in account all parameters is indicated.

In general, a geometric correlation between the hardness and the mean arithmetic height by varying the tool distance d could not be proved, a direct relationship could not be drawn. The influence of the same tool distancing on the materials was shown. As an outlook, the findings need to be connected in detail using other methodologies in further investigations. The connection between surface changes by contact pressure and forming effects by tension, compression and bending need to be separated in detailed investigations and step by step. This would also help to improve simulations and also to identify the contact pressure height and its distribution. On the experimental side, an idea would be to preload materials with a specific tool radius only and calculate the Hertzian stresses and the final surface parameters. The following hardness and surface changes could be combined with the results above. Comparing the materials, higher specific retention forces seem to lead to higher surface changes, what might be due to the contact pressure. The interaction between the mechanical and tribological system represented by the surface values seems to interact in a complex way that needs to be investigated furthermore.

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