Influence of a drawbead passage in deep drawing processes on surface values and the tribological system

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Abstract. In recent times, lightweight design and functional integration in metal forming and especially in deep drawing operations lead to complex geometries. These geometries can cause variable defects in production. Especially with modern materials like AHSS or UHSS, deep drawing becomes more challenging. One common way to meet these challenges and manufacture sheet metal parts without defects is the application of drawbeads in the forming tool. Drawbeads are used for an exact control and forecast of the material flow during the deep drawing process. It was already shown, that different material parameters like the tensile strength and the fracture strain are changed significantly after running through a drawbead. In addition, there are various indications that the tribological system in a drawbead passage is also changed significantly and that this has further influence on the ongoing drawing process. This assumption is examined with an experimental setup derived from industrial deep drawing processes. Therefore, different sheet metal materials are drawn through a drawbead geometry under the same conditions like the blank holder force, the drawing velocity or lubrication. After the drawbead passage, 3D surface parameters are measured and compared to the values in its initial state. Following, conventional strip-drawing tests with preloaded strips are carried out. The variation of the friction coefficient after a drawbead passage is analysed and compared to the initial state. The results are correlated with the surface values. For these investigations, three different materials are used: a conventional deep drawing steel because of its wide application as well as an advanced high strength steel AHSS and an aluminium alloy of the 6xxx series as representatives for modern lightweight materials.

1. Introduction

In modern forming processes like deep drawing of metal parts, functional integration and complex design are more present than ever before [1]. This leads to demanding and challenging geometries which can cause multiple defects and failure in production series. Especially for the new developed high strength steel classes and modern aluminium alloys, deep drawing becomes more challenging. One option to address these challenges is the accurate control of the material flow during the forming process. Next to changes in the lubrication system and different tool coatings also an adjustment of the blank holder force can be done according to Doege [2]. Very often, high retention forces are needed in the different forming areas and drawbeads are the method of choice as they can be implemented directly in the tools. Next to the retention forces, they also affect other areas in the forming process. It could already be shown by the authors in [3], that mechanical properties such as the yield stress or the
uniform elongation \( \varepsilon_u \) are changed after a drawbead passage and that this affects the forming process. There are also optical indications, that the tribological system after a drawbead is changed and this may influence the metal forming.

In 1902, Stribeck [4] found a connection between the velocity and the friction coefficient which is still known as the “Stribeck curve” today. It was also investigated, that the friction coefficient is a function of many more parameters [4]. Nowadays, it is well known, that the contact pressure in the friction area affects the tribological system, which is for example analysed by Zöller in [5]. In addition, it is found that the velocity, the lubrication system and the tool and sheet metal parameters influence the tribological conditions in general [6].

Filzek investigated in 2004 [7], that in the drawbead geometry the contact pressure and other parameters are changed significantly in comparison to the rest of the forming area, which indicates a distinct change of the friction coefficient. Also Christiany and Groche analysed in a strip drawing test with drawbead and the use of Advanced High Strength Steels (AHSS), that different tool materials lead to different wear resistance and therefore also to different tribological conditions [8]. Ludwig [9] and Leocata [10] investigated the friction coefficient only for one material deep drawing steel and aluminium, but not under same conditions and did not consider the different sheet metal sides. In general, this is not considered in simulations by using one global friction coefficient. Hol and Wiebenga implemented a commercial system to forecast friction coefficients under different conditions by using a multi-scale model [11]. This could prove a good accuracy to standard friction tests [12]. Summarized, a change of the tribological system in a drawbead passage is assumed and should be analysed. Therefore a modified strip drawing test with drawbead geometry, which setup was also presented by the authors in [3], is used to preload steel and aluminium sheet metal in a drawbead passage. Afterwards, conventional strip drawing tests are done with the preloaded material from the drawbead to investigate the friction behaviour after a drawbead treatment and especially to analyse the influence of the changed surface properties. The transformations of the friction coefficients are compared to the measurements in the initial state. For a widespread investigation, 3D confocal analysis of the sheets are done before and after the drawbead pass to correlate the profile result and the tribological conditions.

2. Materials

In modern deep drawing processes, many different material grades are used to fulfil the multiple challenges in forming processes. To provide an overview on the different sheet materials, three varying sheets are used for this investigation. First, the aluminium alloy EN AW AA6014 according to EN 573-1:2005-02 is investigated in T4, which means the material was annealed and naturally aged to a stable state. This alloy is widely used in bodyshell applications and for structural components in the automotive industry [13]. Apparently, aluminium is also considered as a lightweight material because of its low density and its high specific strength compared to steel sheets. Additionally, a conventional mild steel CR 3 GI 50/50-U according to VDA 239-100 [14] is investigated. It is hot dip zinc coated with 50 g/m² on each side and is considered because of its wide application in the industry. It is also widely known as DC04. Finally, the AHSS CR 440Y780T-DP GI40/40 [14], is analysed because of its application as a high strength steel in modern lightweight design, especially in the automotive industry and will be called DP800 in this publication. All materials are used in the initial thickness of \( t_0 = 1.0 \text{ mm} \) to make them comparable.

As it can be seen in Table 1, results from the optical 3D uniaxial tensile tests are differing between the sheets. As expected the AHSS DP800 has a way higher tensile strength TS compared to the aluminium alloy while DC04 and AA6014 have a higher uniform elongation \( \varepsilon_u \) in comparison.

Additionally, 3D surface parameters are measured by a confocal microscope (Nanofocus) in the initial state according to [15] and were averaged over the two different sides. Pfestorf and Staeves already found in 1997 different area roughness parameters of metal sheets [16] to be important for the lubrication system in deep drawing processes. In this work, two parameters are chosen: the mean
arithmetic height of the area $S_a$ to quantify the surface globally and the closed void volume $V_{Cl}$ as an attribute to quantify the oil storage ability of the sheet metal. Analysing the surface parameters in Table 1, a correlation between the values $S_a$ and $V_{Cl}$ is evident. Aluminium has a quite smooth surface testified by $S_a$ of 0.8 µm with a layer of aluminium oxide resulting from oxidation processes. Next to this, the DP800 steel with the zinc coating has a mean arithmetic value of $S_a$ of 1.18 µm and is comparable. The mild steel DC04 has a higher roughness of $S_a = 2.45$ µm.

**Table 1.** Material parameters in uniaxial tensile test and 3D surface parameters with corresponding standard deviations in the initial state before preloading

| Material  | Yield Strength YS [MPa] | Tensile strength TS [MPa] | Uniform elongation $\varepsilon_u$ [%] | Mean arithmetical height $S_a$ [µm] | Closed void volume $V_{Cl}$ [mm$^{-1}$] |
|-----------|------------------------|---------------------------|--------------------------------------|--------------------------------------|---------------------------------------|
| AA6014    | 141.9 ± 1.1            | 249.6 ± 1.7               | 20.0 ± 0.2                           | 0.81 ± 0.07                          | 436.2 ± 19.7                          |
| DC04      | 165.0 ± 0.5            | 303.7 ± 0.3               | 25.7 ± 0.6                           | 2.45 ± 0.22                          | 1576.8 ± 235.1                        |
| DP800     | 505.4 ± 1.9            | 808.2 ± 3.4               | 12.9 ± 0.3                           | 1.18 ± 0.10                          | 597.3 ± 19.8                          |

All parameters are used to compare the different sheet metal materials in the initial state and after a preloading by a drawbead.

3. **Experimental setup and applied methodology**

For the preloading with a drawbead, a conventional strip drawing test setup with a drawbead geometry is used. The methodology for the test setup is shown in Figure 1.

**Figure 1.** Applied methodology with drawbead preloading followed by 3D confocal surface measurements in and strip drawing tests with preloaded sheet metals.

The used drawbead has a radius of 6.5 mm and a height of 5.0 mm according to the Numisheet Benchmark 2008 [17]. In the first step, a strip with the geometry of 40 mm x 750 mm for steel materials and 58 mm x 750 mm for aluminium is cleaned with acetone and afterwards lubricated to 2.0 ± 0.1 g/m² by using the spot oil KTL N 16 (Zeller+Gmelin GmbH & Co. KG). The amount of lubrication is controlled by an oil film gauge Infralytic NG2 (Infralytic GmbH) [18]. The strip is then clamped into the drawing unit and the tool is closed with a blank holder force according to the pressure of 7.5 MPa to the projected parallel area. Afterwards, the strip is pulled through the drawbead with a velocity of $v = 50$ mm/s and the normal force is controlled. The remaining oil is measured on both sides of the preloaded sheet. Afterwards, the preloaded specimen is cut in two parts by a laser cutting. This is done to avoid any damages or scratches by the following strip drawing test on the measurement area. This can also be seen in Figure 2 a).
The one part of the preloaded specimen is examined in the confocal microscope NanoFocus μSurf (Nanofocus AG) with a 20 x objective and a Gaussian filter is applied onto the data. Thus, on the inner and outer side of the drawbead three measurements for each side \( n_m = 3 \) with a size of 3 mm x 3 mm are done and averaged for each side. This is applied to testify that there are no deviations over the strip width. This procedure is repeated for at least five specimen \( n_s = 5 \) and the surface values \( S_{a} \) and \( V_{Cl} \) are averaged and can then be compared to the initial state in section 2.

![Confocal measurements area](image)

Figure 2. a) Details of three measurement areas for each side and b) evaluated surface parameters mean arithmetic height \( S_{a} \) and closed void volume \( V_{Cl} \) according to [16]

Afterwards, conventional flat strip drawing tests are performed to analyse the friction coefficient of the preloaded sheets. This is tested on tool made of 1.2379 with a tool size of 55 mm x 100 mm and the sheet is fully covered by the tool surface. In preliminary studies, it was investigated that for preloaded aluminium heavy abrasion takes place on the edges and the friction coefficient could not be determined. It was decided to laser cut the aluminium strip to a width of \( w = 40 \) mm from \( 58 \) mm before. In this step, all preloaded material strips have the same width of \( w = 40 \) mm. To analyse the influence of the surface changes and separate this from the lubrication system and different remains on the sheets after a drawbead, the strips are cleaned with acetone and re-lubricated with KTL N 16 oil to \( 2.0 \pm 0.1 \) g/m² as before. This is done with the intention to separate the influence of the lubrication from the surface changes in a drawbead, which is shown in section 4.2. Afterwards, \( n_s = 5 \) specimens are drawn through the flat tool and the friction coefficient is evaluated according to a test setup following VDA 230-213 [19]. The corresponding blank holder pressure for friction tests is set to \( p_N = 2.5 \) MPa to avoid any tendencies to abrasion. The drawing velocity is defined to \( v = 50 \) mm/s taking into account the preloading with the same velocity. To avoid further influences of the preloaded edges, they were deburred manually before testing.

4. Results and analysis

In this section, the results of the confocal measurements and the strip drawing tests with preloaded specimen are described. As could be also shown by the authors in [3], the mechanical properties and the retention forces for the identical test setup can be assumed as constant.

4.1. Confocal measurements of sheets preloaded in a drawbead passage

In Figure 3, the analysis of the chosen surface parameters are presented. On the left hand side, Figure 2 a), the arithmetic mean height \( S_{a} \) can be seen in the initial state and after preloading for the in- and outside of the drawbead. In the initial state, a difference between the different materials is visible as noted in Table 1. Also, a smoothing for the steel materials after the drawbead can be seen.
directly. This smoothing effect is more significant on the inside of the sheet metal that passed the drawbead. For the aluminium alloy AA6014, a constant value of $S_a$ or a kind of roughing of the outside is detected. This is in contrast to the results of the steel materials used.

As $S_a$ only shows a global overview of the surface characteristic, in Figure 2 b) the closed void volume $V_{Cl}$ can be compared in initial state and after preloading. This value reflects the ability of sheet metal surfaces to store lubrication. The original state can be correlated to the initial state of $S_a$, but the development after preloading the sheets is differing. While the $S_a$ value of AA6014 is rising on the outside, the closed void volume $V_{Cl}$ stays nearly constant or is even reduced on the inside. This indicates a loss of the lubrication storage ability with a significant roughening of the global value $S_a$ at the same time.

For the steel materials DC04 and DP800, a significant reduction of the closed void volume $V_{Cl}$ is visible, especially for the AHSS DP800. The oil storage ability becomes lower, in particular on the outside. To give a qualitative comparison in Figure 4, the 3D profile height of the different sheet metal materials in the initial state and after the drawbead preloading is shown.

Especially for the aluminium AA6014, it is obvious that the surface got valleys or fine cracks in the area perpendicular to the rolling and drawing direction. The outside of the drawbead here is affected more, which is also analyzed in the results of $S_a$ and $V_{Cl}$ in Figure 3. The surface profiles for DC04 and DP800 in the 2nd and 3rd row show a significant smoothing, that also certifies the findings before. Also here, a difference between the inside and outside is determined. As conclusion for the confocal microscopy of sheet metals preloaded in a drawbead, it can be stated that AA6014 is roughened and fine valleys appear perpendicular to the drawing direction. For the steel sheets, a smoothing is visible and the lubrication storage ability is for example limited down to 25 % for DC04. This illustrates the surface changes happening in a drawbead.
4.2. Strip drawing tests with preloaded sheet metal

Next to the confocal microscopy, strip drawing tests with preloaded specimens after a drawbead passage are performed. Thus, the preloaded specimen are cut to a suitable length. In Figure 5, the corresponding results of the friction coefficient in the initial state and after a drawbead preloading with the recorded test parameters are presented.

In the initial state on the left side of the diagram, AA6014 and DC04 show nearly the same friction coefficient with about $\mu = 0.04$, while the value of DP800 is located around $\mu = 0.06$. The results for the preloaded specimen finally all show significantly higher values. The standard deviations in between the variations is also increased, which could be a consequence of the whole process with many steps, which can influence the results. In comparison to the initial state, the friction coefficient...
of AA6014 rises about 72 %. The preloaded mild steel DC04 shows the most significant change and the value is more than doubled to nearly 120 %. Compared to the other materials, DP800 has the smallest increase of the friction coefficient with only 38 %. Anyway, all friction coefficients tested in the strip drawing test after preloading in a drawbead are notably higher than before, although the lubrication was renewed after the drawbead passage. It can be shown that carrying out strip drawing tests without changing the lubrication condition after the drawbead test leads to even greater values of the friction coefficient.

5. Discussion

In this section, a detailed examination of the results presented in the chapters before will be done and possible explanations for the material behaviour shall be found. Comparing the surface parameters in Figure 3 and the friction coefficients after preloading in Figure 5, a correlation between the reduction of the closed void volume $V_{Cl}$ and the modification of the friction coefficients $\mu$ is displayed as a function of the ratio parallel normal pressure $p_N$ to the Yield Stress YS.

An important finding is, that the most distinctive reduction of the oil storage ability for the sheet metal DC04 is accompanied with the most significant increase of the friction coefficient. As the lubrication is renewed to 2.0 g/m², the influence of the surface change is isolated. In comparison, the surface parameters of DP800 are not reduced in the same amount. This can also be seen in the lower increase of the friction coefficient after the drawbead passage. It needs to be mentioned, that both steel materials have a zinc coating with 50 g/m² for DC04 or respectively 40 g/m² for DP800. This also has influences on the forming process, which is also mentioned by Murakawa et al. in [20].

Aluminium alloys have an oxide layer, and show under tensing with bending a different behaviour on the in- and outside, which was analysed by Azushima et al. [21]. This behaviour can also be responsible for the roughening of AA6014 surfaces after the drawbead passage.

As the blank holder pressure is responsible for the contact pressure and the tool distance in the drawbead area, a different behavior of the three materials at the same load was expected. As the YS is a characteristic to determine the onset of yielding, a connection between the blank holder pressure, the YS and the material behavior in a drawbead is assumed. This means, the same blank holder pressure $p_N$ is expected to have higher impact on materials with a lower YS, for example in comparison between DC04 and DP800. This assumption was analyzed with the existing data. In Figure 6, the friction coefficient $\mu$ is displayed over the ratio $p_N / YS$ (blank holder pressure $p_N$ and yield strength YS).

![Figure 6](image_url)

*Figure 6. Rise of friction coefficient after drawbead vs. the ratio $p_N / YS$ (blank holder pressure $p_N$ and yield strength YS)*
As explained, this ratio is an individual index for the loading for each material in the drawbead. A linear correlation is drawn on the diagram, but shows a poor coefficient of determination with \( R^2 = 0.40 \) whereas a polynomial in three points, of course, can be fitted perfectly.

There are different explanations for this. First of all, the materials have different coatings and therefore frictional behaviour. The aluminium alloy has an oxide layer and shows a roughening compared to the steel materials with a zinc coating. One more aspect is the combination between the applied blank holder pressure \( p_N \) and the resulting gap between the die and blank holder (see also Figure 1). Depending on the sheet metal material, a constant blank holder pressure leads to a corresponding distance between the tools. This, of course is followed by different contact pressure in the radii areas, which are mainly responsible for smoothing or roughening of the materials. On the inside peak of the drawbead, the contact pressure for example is quite high, which explains the higher smoothing for most materials on the inside. Next to this, it needs to be mentioned that the drawing oil was renewed in the strip drawing tests. The assumption of a linear correlation could not be proved here, more experimental data is necessary.

One aspect that was not considered in this evaluation yet is the removal of oil during the forming process in the drawbead. By oil film thickness measurements after the drawbead passage on each side with help of the InfraLytic NG 2, it is testified that a significant reduction of lubrication is happening as is displayed in Figure 7. As already mentioned in section 3, the initial lubrication is set to 2.0 \( \text{g/m}^2 \) and is measured with a low standard deviation for all materials on the in- and outside before the preloading by a drawbead. For the aluminium alloy AA6014, a reduction of less than 0.2 \( \text{g/m}^2 \) was found on the inside. The value on the outside is even a little bit lower. In comparison, the oil film thickness for DC04 is analysed to 1.0 \( \text{g/m}^2 \) on the inside and 0.6 \( \text{g/m}^2 \) on the outside. For DP800, the same trend occurs with a reduction on the inside to 1.0 \( \text{g/m}^2 \) and lower than 0.5 \( \text{g/m}^2 \) on the outside. This distribution seems to be quite the opposite of the development in Figure 3, where the smoothing on the inside is higher whereas the oil reduction is more evaluable on the outside. This fact need to be checked with respect to the original oil film thickness after the drawbead passage. Thus, a process without re-lubrication needs to be developed.

![Figure 7. Lubrication measured before and after a drawbead passage](image)

### 6. Summary and outlook

In this publication, strip drawing tests with drawbead geometry were performed with three different sheet metal materials. Thus, a drawbead according to Numisheet Benchmark 2008 and a height of \( h = 5 \text{ mm} \) was used with a velocity of \( v = 50 \text{ mm/s} \) and a blank holder pressure of \( p_N = 7.5 \text{ MPa} \). In the next step, the preloaded area of the specimen was examined by confocal microscopy. The surface parameters \( S_a \) and \( V_{Cl} \) were analysed in the initial state and after preloading in a drawbead. Following
this, strip drawing tests with preloaded specimen were performed with a re-lubrication to 2.0 g/m² to separate the influence of the surface changes. This process is also schematically shown in Figure 1.

The most distinctive findings in this paper are:

- Steel materials DC04 and DP800 are smoothed after a drawbead passage, especially on the inside. This can be testified by the evaluation of the arithmetic mean height $S_a$ and the closed void volume $V_{Cl}$ in confocal microscopy.
- In contrast, the aluminium alloy AA6014 is roughened by an alternating bending process.
- For all sheet metals, the friction coefficient is increased after a drawbead passage between 39 % and 119 %, although the sheet metal is cleaned and re-lubricated to 2.0 g/m² again. This shows the influence of the drawbead preloading on the friction coefficient, which is also emphasized by the surface changes analysed.
- A correlation between the blank holder pressure $p_N$ in combination with the yield strength $Y_S$ and the friction coefficient $\mu$ shows a linear correlation.
- After the drawbead, the lubrication is reduced heavily and is also depending on the side.

It is shown, that a drawbead passage has significant influences on the 3D profile of preloaded surfaces. By separating the lubrication system, influence of the surface variation was shown in subsequently performed strip drawing tests and the evaluation of the friction coefficients. For further investigations, an evaluation with the present oil film thickness after a drawbead is indicated. Thus, the process needs to be re-developed to investigate preloaded specimen with the same conditions. It would be also interesting to analyse variations of the blank holder pressure $p_N$, the drawbead geometry like the radius or the drawbead height or the drawing velocity. Also, the strip drawing test for friction coefficients can be done at different pressure or velocities to develop more complex friction models. These results could also be implemented in numerical models with drawbeads.

In this paper, the investigations were done with a with a constant pressure $p_N$ or blank holder force $F_N$, which lead to different gaps between blank holder and die for each material. According to this, a comparison must take this into account. The most interesting finding is the behaviour of each single material compared to its initial state. Another comparison could be done, when the drawbead passage is processed with a constant distance between the tools that guarantees the same geometrical conditions for all material, although this might have other influences. A further analysis of surface parameters and the friction coefficient would help to understand the tribological processes that occur in a drawbead in detail.

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