Investigation of the influence of process parameters on adhesive wear under hot stamping conditions

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Abstract. Current challenges like increasing safety standards and reducing fuel consumption motivate lightweight construction in modern car bodies. Besides using lightweight workpiece materials like aluminum, hot stamping has been established as a key technology for producing safety relevant components. Producing hot stamped parts out of ultra-high strength steels offers the possibility to improve the crash performance. At the same time the weight of car structure is reduced by using thinner sheet thicknesses. In order to avoid oxide scale formation and ensure corrosion protection, AlSi coatings are commonly deposited on the sheet surfaces used for direct hot stamping. This workpiece coating has a critical impact on the tribological conditions within the forming process and, as a consequence, influences the quality of hot stamped parts as well as tool wear. AlSi coatings have been identified as major reason for adhesive wear, which represents the main wear mechanism in hot stamping. Within this study, the influence of the process parameters on adhesive wear are investigated in dependency of workpiece and tool temperatures, drawing velocities and contact pressures. The tribological behavior is analyzed based on strip drawing experiments under direct hot stamping conditions. The experiments are performed with AlSi coated 22MnB5 in contact with the hot working tool steel 1.2367. For analyzing the amount of adhesion on the friction jaws, the surfaces are characterized by optical measurements. The experiments indicate that higher workpiece temperatures cause severe adhesive wear on the tool surface, while an increase of drawing velocity or contact pressure led to reduced adhesion. The measured friction coefficients decreased with rising amount of adhesion and remained at a constant level after a certain adhesive layer was built up on the tool surface.

1. Introduction
Nowadays, hot stamping of boron manganese steel grades, typically 22MnB5, is a commonly used technology to produce high-strength and safety relevant components for modern car bodies. The process combines forming at high temperatures with a quenching process in one step [1]. Thus, body parts with a tensile strength up to 1500 MPa can be manufactured with high accuracy because of reduced springback [2]. Due the high reachable strength of hot stamped components, a reduction in sheet thickness is possible while ensuring the necessary crash performance. Thus, the weight of modern car bodies can be reduced, simultaneously increasing the passenger safety [3]. Hot stamping can be divided into direct and indirect hot stamping. Within direct hot stamping, the blank is heated up in a furnace at temperatures between 880 °C and 950 °C. After the austenitization the blank is formed and simultaneously quenched in the press and cut to the final geometry [4]. Contrary to that, the blank is formed at room temperature within indirect hot stamping, followed by an austenitization and a
quenching step [5]. To reach a fully martensitic microstructure, a minimum cooling rate of 27 K/s has to be ensured during the forming. For preventing an oxidation of the blank during the heat treatment and the forming, coatings are applied to the workpiece. While Zn coatings are mainly used for the indirect hot stamping process because of their favorable forming behavior at room temperature, AlSi coatings are applied for direct hot stamping [6]. Due to the high forming temperatures within hot stamping, commonly no lubricants are used. This results in high amounts of wear caused by high thermal and mechanical loads. The two dominant wear mechanisms within hot stamping are abrasive wear and adhesive wear [7]. Abrasive wear occurs due the relative movement of two solid bodies with different hardness. The roughness peaks of the harder body or abrasive particles penetrate the surface of the softer body. Adhesive wear on the tool surface is mainly caused by AlSi [7]. In order to provide a constant quality of hot stamped parts, time and money consuming maintenance of the surface of hot stamping tools is necessary regularly. Therefore, a deeper understanding regarding the cause-effect relations between the hot stamping process and adhesive wear is needed for developing wear reducing measures. Kondratiuk et al. [7] performed cup drawing experiments to characterize the adhesive wear on the die surface. However, within this study the influence of the process parameters could not be analyzed separately. Furthermore, adhesive wear on the tool surface was analyzed by Ghiotti [6] based on pin-on-disc tests. Although these tests provide the possibility to analyze the influence of the process parameters on the wear behavior selectively, the tribological conditions of industrial hot stamping applications can hardly be reproduced with pin-on-disc tests according to [5]. Thus, within this context strip drawing experiments are carried out under hot stamping conditions for analyzing the influence of workpiece temperature, drawing velocity and contact pressure on adhesive wear.

2. Experimental setup

2.1. Tool and workpiece material.
Tool materials for hot stamping face high mechanical thermal loads. Besides the thermal conductivity, wear resistance is a critical characteristic for hot stamping tools. Due to its characteristics, the tool steel 1.2367 (X38CrMoV5-3) is commonly used for industrial hot stamping applications [8]. Within this study, this steel grade is used as tool material with a hardness of 53 HRC. The ground surface has a roughness of $Ra = 0.60 \pm 0.02 \mu m$ and $Rz = 4.95 \pm 0.19 \mu m$.

As workpiece material, the 22MnB5 with AlSi coating has been chosen, representing the most common used workpiece material for hot stamping components. After being hot stamped, components produced out of 22MnB5 reach a tensile strength up to 1500 MPa due to its chemical composition [9]. Within this study, the 22MnB5 has been used coated with an AlSi coating with 150 g/m². The material is heat treated at a furnace temperature of 930 °C for 360 s, according to supplier recommendations. After the heat treatment and being quenched at air, the surface of the workpiece has a roughness of $Ra = 1.94 \pm 0.1 \mu m$ and $Rz = 11.70 \pm 0.3 \mu m$.

2.2. Flat strip drawing test rig
For analyzing the tribological conditions under hot stamping conditions a strip drawing test rig has been developed. The test rig is designed to examine the influence of the process parameters tool temperature, workpiece temperature, drawing velocity and contact pressure on friction and wear within hot stamping. Figure 1 illustrates the test rig (Figure 1a) and the functional principle of a one-sided strip drawing experiment (Figure 1b). Normal and tensile forces are created by two hydraulic cylinders. Due to the heatable slide and an infrared camera, constant workpiece temperatures are ensured before performing the strip drawing experiment. The process parameters can be examined isolated, thus the cause-effect relations between the prevailing parameters and the resulting tribological behavior can be analyzed. Test rig and experimental procedure are described more in detail in [10].
2.3. Experimental procedure
The influence of process parameters on adhesive wear under hot stamping conditions has been investigated with one-sided flat strip drawing experiments. The tests were performed for varying workpiece temperatures, contact pressures and drawing velocities since previous studies showed a significant influence of these parameters on the frictional behavior [11]. For analyzing a qualitative effect of the mentioned parameters on the wear behavior, the influence of the extreme values of the test parameters on wear is compared. The experiments were repeated three times (n = 3). After conducting the experiments, the contact surfaces of the friction jaws have been characterized optically for analyzing the amount of adhesive wear in dependency of the process parameters.

![Figure 1. Flat strip drawing test rig.](image)

2.3.1. Strip drawing experiments. After the austenitization the strip is transferred manually from the furnace to the heated slide. By controlling the strip temperature with an infrared camera, the nominal strip temperature is adjusted. Within the evaluation area over a distance of 100 mm, the strip temperature is homogenous with a deviation of ± 10 °C. When reaching the nominal temperature, the contact pressure is applied by the normal force cylinder and the drawing movement is initiated. The drawing velocity remains at a constant nominal value within the evaluation area. Table 1 illustrates the examined process parameters.

| Minimum value | Maximum value |
|---------------|---------------|
| Tool temperature (in °C) | RT | - |
| Strip temperature (in °C) | 530 | 700 |
| Contact pressure (in MPa) | 2.5 | 7.5 |
| Drawing velocity (in mm/s) | 30 | 120 |

The strip drawing tests are performed with unheated friction jaws (room temperature). The strip temperature is varied between 530 °C and 700 °C, representing a typical range of temperature where the forming takes place in industrial hot stamping processes. The contact pressure has been tested between 2.5 MPa and 7.5 MPa, as this range of contact pressure has been identified as relevant for industrial hot stamping applications. Drawing velocities have been analyzed between 30 mm/s to 120 mm/s presenting the maximum range of the test rig. The influence of the process parameters was analyzed respectively based on the two extreme values of the presented test parameters leading to qualitative results about the tribological behavior.

2.3.2. Determination of adhesive wear. To analyze the cause-effect relations between the tribological behavior and the process parameters, the tool surface has been characterized optically before and after the experiments. The measurements were performed with confocal microscopy on a
NanoFocus “μSurf” microscope. Figure 2 illustrates the geometry and the surface topography of an unworn friction jaw. By characterizing the surface of the friction jaw optically after the strip drawing experiments the amount of adhesive wear is analyzed qualitatively.

![Unworn tool surface](image)

| Friction jaw | Confocal microscopy |
|--------------|---------------------|
| Tool material | 1.2367 |
| Drawing direction | Lens 20x |
| Orientation | Polynomial 2nd degree |

**Figure 2. Optical surface characterization of friction jaw.**

3. Results

3.1. Influence of workpiece temperature.

The influence of the workpiece temperature on adhesive wear has been investigated with an unheated friction jaw and 2.5 MPa contact pressure. The drawing velocity was set to 50 mm/s, which represents a mid value of the process window leading to robust experiments. The experiments were conducted with 530 °C and 700 °C workpiece temperature. Figure 3 illustrates the measurements of the worn friction jaw surface after 1, 2, 3 and 10 performed experiments and the measured mean friction coefficients.

![Workpiece temperature](image)

**Figure 3. Influence of workpiece temperature on adhesive wear and frictional behavior.**
The surface measurements indicate increasing wear on the tool surface with increasing number of experiments. This wear has been identified as Al adhesion via rem-measurements, containing a minimal percentage of Si. However, after 3 and 10 experiments significantly more adhesive wear can be found on the surface of the friction jaw for 700 °C workpiece temperature. This could be explained by the diffusion rate which is strongly temperature dependent, as discussed in previous studies [12]. Thus, high temperatures would increase the material transfer due to an increased diffusion rate.

Besides the adhesive wear, the frictional behavior has been analyzed. In general, the influence of the workpiece temperature on the friction coefficient conforms with previously conducted studies [11]. Higher workpiece temperatures led to a decreased friction. Furthermore, the measured friction coefficients decreased continuously during the first three experiments and remained at a constant level after the fourth experiment. Thus, decreased friction coefficients were measured with increasing amount of adhesive wear for both tested workpiece temperatures. This could be due to two reasons. The high temperatures in the contact zone are near or already above the melting point of Al. Thus, the thin adhesive Al layer on the surface of the friction jaw could cause a lubricating effect due to the reduced tensile strength of Al. Furthermore, since adhesion is a diffusion based process, first adhesive Al particles could reduce further material transfer, which was also reported in previous studies [13], leading to a reduced friction. However, the experiments show that the thickness of the adhesive layer on the friction jaw surface grows with increasing number of performed strip drawing tests, leading to increased surface roughness. Therefore, the lubricating effect of the Al adhesion would be undone after reaching a certain value of adhesive wear.

3.2. Influence of drawing velocity.
The wear behavior in dependency of the drawing velocity has been characterized at a workpiece temperature of 600 °C and 2.5 MPa contact pressure. The strip drawing tests were carried out with 30 mm/s and 120 mm/s with an unheated friction jaw. Figure 4 shows the results of the experiments regarding the tribological behavior for the two different analyzed drawing velocities. Again, as seen before in chapter 3.2.1, an increasing number of conducted experiments causes increasing amount of adhesive wear on the surface of the friction jaw.
After 3 and 10 performed experiments, a drawing velocity of 30 mm/s causes significantly more adhesive wear compared to the experiments with 120 mm/s drawing velocity. This could be due to two reasons. It has been reported that adhesion is a time dependent process [14]. Thus, the increased contact time between workpiece and friction jaw at 30 mm/s leads to a bigger amount of adhesive wear. Furthermore, the observed wear behavior could be explained by the experimental setup. The workpiece temperature is controlled actively by heating elements on the moveable slide to ensure homogeneous temperatures within the evaluation area. Therefore, lower drawing velocities could lead to an increased heating of the friction jaw which would subsequently cause higher temperatures within the contact zone between workpiece and friction jaw. Analyzing the frictional behavior again an increasing amount of adhesive wear seems to decrease the measured friction coefficients for both investigated drawing velocities within the performed experiments.

3.3. Influence of contact pressure.

The influence of the contact pressure on the wear behavior has been analyzed for a drawing velocity of 50 mm/s and a workpiece temperature of 600 °C with an unheated friction jaw. The experiments have been performed with 2.5 MPa and 7.5 MPa. Figure 5 illustrates the characterized surfaces of the friction jaw after 1, 2, 3 and 10 performed experiments.

![Figure 5. Influence of contact pressure on adhesive wear and frictional behavior.](image)

The frictional behavior is illustrated in dependency of the number of experiments. As already shown for the experiments with varied workpiece temperature and drawing velocity, an increasing number of experiments causes rising amount of adhesive wear on the surface of the friction jaw. After 3 and 10 experiments, a higher amount of adhesion could be measured for 2.5 MPa, whereas experiments with 7.5 MPa created less adhesive wear. Again, this could be explained with the resulting temperature in the contact zone between friction jaw and workpiece since the heat conduction increases with rising contact pressure. Thus, high contact pressures reduce the temperature in the contact zone due to increased heat dissipation by the friction jaw.
The analyzed frictional behavior in dependency of the contact pressure conforms to previous investigations [12]. Due to increased contact pressures, decreased friction coefficients were measured. Again bigger amounts of adhesive wear seem to cause reduced friction for both investigated contact pressures, which could already be observed for the tested drawing velocities and workpiece temperatures.

4. Discussion
The experiments that have been performed within the scope of this study showed that increasing workpiece temperatures cause increased adhesive wear, whereas increasing drawing velocity and contact pressure lead to decreased adhesion on the tool surface. The influence of the workpiece temperature and drawing velocity on adhesive wear has been investigated by Tian et al. [14] with strip drawing tests. Within this study increasing adhesive wear is caused by increased workpiece temperatures. The amount of adhesive wear on the tool surface was more distinctive for slow drawing velocities. Based on these results, high stamping velocities could lead to a reduction of the wear of hot stamping tools in industrial applications. Additionally, a previous cooling of the blank prior to the forming motion could possibly show potential for reducing die wear. Further investigations performed by Ghiotti et al. [6] based on pin-on-disc tests indicated severe adhesive wear at testing temperatures of 600 °C and 700 °C. They explained the observed behavior with the diffusion phenomena of Fe and Al which are strongly influenced by the temperature. Several investigations like [15] and [16] measured increased adhesive wear due to increased contact pressure, which would contradict to the results of the current study. However, it has to be pointed out that the referenced studies observed the increased adhesive wear at the die radius. Thus, the increased adhesion could have been caused predominantly by the bending of the workpiece, leading to cracks in the coating.

Besides the influence of hot stamping process parameters on adhesive wear, the frictional behavior has been analyzed for different amounts of adhesion on the tool surface within the current study. The measured friction coefficients decreased continuously during the first three experiments and remained at a constant level after the fourth experiment, while the adhesive wear on the friction jaw surface increased with a rising number of performed experiments. On the one side, this behavior could be explained by the high temperature in the contact zone near or above the melting point of Al leading to a lubricating effect of thin adhesive Al layers. Kondratiuk et al. [7] performed strip drawing tests investigating the frictional behavior within hot stamping. During the conducted experiments a significant decrease of the friction coefficient from a high level to a steady frictional state could be observed. This would confirm the assumption regarding the lubricating effect of the Al layer on the friction jaw surface. On the other side, they explained this behavior due to the initial material transfer caused by adhesive wear. After reaching a certain compact layer, the adhesion decreases leading to a steady friction value. Ghiotti et al. [13] likewise showed that adhesion takes place predominantly at the beginning of the performed pin-on-disc tests, while only a slight increase of adhesive wear could be detected at increasing number of cycles.

5. Summary
Within the scope of this study the influence of workpiece temperature, contact pressure and drawing velocity on adhesive wear and the resulting frictional behavior has been analyzed. The strip drawing tests have been performed with 530 °C to 700 °C workpiece temperature, 2.5 MPa to 7.5 MPa contact pressure and with drawing velocities between 30 mm/s and 120 mm/s. Higher workpiece temperatures caused severe adhesive wear on the tool surface, while an increase of drawing velocity or contact pressure led to reduced adhesion. The measured friction coefficient decreased with rising amount of adhesion and remained at a constant level after a certain adhesive layer was built up on the tool surface.
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