The influence of coating porosity on friction and wear during hot stamping of AlSi coated ultra-high strength steel

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Abstract. Hot stamping is a forming process widely used in the automotive industry. Severe adhesive tool wear occurs in the hot stamping process. Hot friction draw tests are performed to investigate the influence of the coating porosity on friction and wear. No relationship is observed between the amount of coating porosity and friction. The results indicate that higher coating porosity leads to a higher amount of wear. However, the type and distribution of the intermetallics in the coating seems to be a more important factor regarding wear. A coating with very high porosity can have relatively low amount of adhesive tool wear if another distribution of phases is present.

1. Introduction
Hot stamping is a non-isothermal process which is used to produce structural automotive parts, see Figure 1. A sheet is heated, transported, pressed at high temperatures (typically 700-750 °C) and directly quenched. In this way, high strength parts (~1500 MPa) are obtained with relatively good formability and low spring back. Often the blanks are coated with an AlSi coating to avoid scaling and have corrosion protection. The AlSi coating undergoes a diffusion process in the furnace, in which several Al_{x}Fe_{y} intermetallics are formed [1]. These intermetallics have a high hardness and brittle behaviour. Windmann [2] measured the hardness of the different intermetallics as function of temperature. AlFe has a significantly lower hardness and higher fracture toughness than Al$_5$Fe$_2$. The authors also showed that the more ductile phase AlFe reduces the abrasive tool wear.

Figure 1. Schematic view hot stamping line.
After heat treatment a brittle coating is obtained with voids and cracks. Chang et al. [3] states that cracks occur even in a deformation-free thermal cycle due the difference in thermal expansion coefficients of the brittle intermetallic phases and the steel substrate. Voids occur directly underneath the oxide, inside the coating and in the diffusion zone. The voids directly underneath the oxide layer are suggested to be caused by two mechanisms. The first mechanism is that two different diffusion processes of Al atoms (Al atoms diffuse to form the oxide layer and Al atoms diffuse to form the Fe-Al intermetallic phases) cause Al vacancies and the agglomeration of these vacancies [3]. Another mechanism is that Al atoms in the AlFe layer react with moisture (present in the furnace) causing the formation of H2 gas [4]. The small voids deeper inside the coating are suggested to be related to the Kirkendall effect and they are not caused by sample preparation as is sometimes suggested [5]. The voids in the diffusion zone are generally considered as Kirkendall voids [6].

Due to the brittle behaviour, the AlSi coating fractures severely during forming which causes severe wear [7-8]. Both adhesive and abrasive wear occur. The adhesive wear can be divided in compaction galling and normal adhesive wear [9]. The compaction galling is severe and exists of fractured coating particles and wear debris which are entrapped at the surface. Accumulation and compaction of these wear particles occurs fast and a transfer layer is formed. A study on B-pillar tools by Vilaseca [10] revealed a thicker adhesive wear layer on the punch (lower tool) than on the die (upper tool) which is believed to be due to the debris which remains on the bottom tool due to gravity. The abrasive wear of the tooling can be caused by the hard AlSi intermetallic compounds of the coating and third body debris such as aluminium oxide particles [2,8,11].

The friction and wear mechanisms in hot stamping are extensively studied [12]. Parameter studies are published, such as effect of temperature [13], pressure [14], tool coatings [15], tool steels [16-18], sliding velocity [19], tool temperature [20] and heat treatments [21]. During the heat treatment both the chemical composition and topography change. The chemical composition of the coating significantly influences the friction and wear conditions [22]. Fracture of the AlSi coating plays a very important role in the abrasive and adhesive wear mechanism [8]. The AlSi coating possesses voids and cracks, which likely influences the fracture behaviour of the coating. However, the influence of the coating porosity on friction and wear during hot stamping is not yet investigated. Therefore, the goal of this study is to understand the effect of coating porosity on friction and wear behaviour during hot stamping.

2. Materials and methods

In order to investigate the effect of porosity on friction and wear during hot stamping, hot strip draw tests are performed, see Figure 2. In the hot strip draw test the sheet is heated in the roller hearth furnace, transported to the friction unit, clamped between two flat tools and drawn through the tools with a constant velocity. The tools are made of uncoated tool steel (EN 1.2367) and have a flat tool surface of 90 x 11 mm. The drawing direction is perpendicular to the grinding direction. The tools are neither heated nor cooled. Five different materials with different amount of porosity in the coating are investigated. Twenty-five strips are drawn consecutively using the same set of tools for each material. A new tool set is used for each material, so that the friction and amount of wear on the tools can be investigated for each material. One test with a very long furnace time is performed to get a huge amount of porosity and a different coating composition. A longer furnace time results in more diffusion of aluminium into steel and as such a lower aluminium content of the coating. Therefore, a different ratio between the several intermetallics is obtained which affects the friction and wear behaviour. Table 1 lists material, tools and process information.

The Coefficient of Friction (COF) is calculated using Coulomb's approach:

\[
\mu = \frac{F_t}{2 F_n}
\]  

In which \(F_t\) is the drawing force and \(F_n\) the normal force. The factor two accounts for this experimental set up since the normal force is applied from the top and bottom. An average COF is calculated from 25 to 150 mm to exclude the effects of static friction and running in issues.
**Table 1.** Test information hot strip draw test.

|                      | Hot strip draw test |
|----------------------|---------------------|
| **Sheet**            |                     |
| Material             | 5 x AlSi coated press hardening steel |
| Dimensions           | 800 x 50 mm         |
| Thickness            | 1.2 – 1.5 mm        |
| **Tools**            |                     |
| Tool material        | 1.2367              |
| Hardness             | 590 HV30            |
| Surface roughness    | 0.20 ± 0.05 µm      |
| **Furnace**          |                     |
| Temperature          | 930 °C              |
| Time                 | 330 seconds or 28 min |
| **Test**             |                     |
| Start temperature    | 700 °C              |
| Velocity             | 100 mm/s            |
| Sliding distance     | ~ 200 mm            |
| Normal force,        | 2.7 kN              |
| Result in nominal surface pressure | ~ 5 MPa |

2.1. Analysis

Several analyses are performed on the tool and sheet surface to unravel the effect of porosity on friction and wear mechanism during hot stamping. The surfaces of the tools and sheets are analysed with 2D stylus (Mahr PKG120) and 3D confocal (nanofocus µsurf mobile) topographical measurements. The tools are analysed after cleaning in an ultrasonic bath (ethanol 10 minutes).

To investigate the porosity, cross sectional analysis is carried out with optical microscopy (Leica DM-LM microscope with a motorised stage (Prior) and a camera (Leica DFC 420C)) and scanning electron microscopy with electron-dispersive X-ray analyser (SEM/EDX, Leo 438VP, EDAX).

3. Results

Hot strip draw tests are performed on five materials which received the same heat treatment in the roller hearth furnace. A longer furnace time is applied on material 3. After the heat treatment, the materials are analysed in cross section to determine the amount of porosity (Section 3.1). Section 3.2 discusses the observed friction and wear mechanism. The influence of the porosity in the coating on the COF is discussed in Section 3.3 and the influence of porosity on tool wear is discussed in Section 3.4.

3.1. Coating porosity

The coating porosity is investigated after heat treatment by SEM analysis including line scans, see Figure 3. The materials are numbered such that an increase in porosity is observed with sample number. Materials 1 to 5 shows approximately the same intermetallic distribution. The diffusion layer thickness (alphaFe(Al) and AlFe) is between 11 and 13 µm, followed by the Al5Fe2 intermetallic. A longer furnace time shows severe porosity and a complete different phase distribution due to the longer diffusion time. The diffusion layer thickness is 27 µm and part of the Al5Fe2 phase has transformed to AlFe (30 weight% Al). The longer diffusion time results in more Al diffusion downwards, thus a thicker layer of AlFe.
3.2. Friction and wear mechanism

After the hot friction draw test flattening and coating fracture are observed in the cross sections, see Figure 4. After applying a normal load, voids directly underneath the surface layer are crushed [23]. The sliding causes ploughing tracks in the coating, which can be observed in the optical topography measurements, see Figure 5.

The topography of AlSi coated steel as delivered, after heating and hot draw testing are shown in Figure 5. Heating results in an increase in roughness. Material 1 has the finest structure and the lowest Sa value. After heating, the roughness increases from Sa 0.59 to 1.95 µm, see Figure 6. The third material has some flattened areas and a roughness of 1.05 µm, which increases a lot (to 2.87 µm) after heating. The fifth material has the coarsest texture and a relatively high Sa (1.88 µm). Thus, the first three materials have comparable and lower roughness (Sa) after the furnace than the materials 4 and 5. The amount of voids and the topography after heating are both related to the diffusion process in the furnace. The amount of voids and the topography of the five materials are different. It is therefore important to be careful to draw hard conclusions on the influence of the voids on the wear, since topography could also play a role. However an indication can be given on basis of the all the results together.

Figure 3. Optical cross sections & line scans for the investigated materials after heating stage.

Figure 4. Optical cross section after HFT 24th sample top side.
The sliding action of the hot friction draw test is visible by the flattening of the surface and ploughing marks. These ploughing marks are caused by galling on the tooling [13]. The ploughing tracks are approximately 5 to 10 µm deep. Longer furnace time results in two times deeper ploughing tracks in the sheet coating. The roughness of materials 4 and 5 shows a larger decrease than materials 1 to 3 (see Figure 6), this could very well be related to the larger amount of fracture of voids directly underneath the surface.

![Figure 5. Optical topography measurements for material 1.](image)

![Figure 6. Topography parameter Sa value. Material 3 long = material 3 with long furnace time](image)

Adhesive and abrasive tool wear are observed. The wear mechanisms after hot friction draw tests were investigated in depth in previous investigation [8]. The adhesive tool wear exists out of normal adhesive wear and compaction galling. Compaction galling is the accumulation of debris compacted on the tooling. Two and three body abrasive wear is observed on the tools. The influence of the coating porosity on tool wear for all materials is discussed in Section 3.4.

### 3.3. Influence of coating porosity on coefficient of friction

Twenty-five strips are drawn consecutively using the same set of tools for each material. Figure 7a shows the COF of each sample during the test series for materials 1, 3, 5 and long furnace time and Figure 7b shows the overall average values for all materials. The COF starts always relatively high for the first sample and then reduces (already in first 5 samples) to a certain level (see Figure 7a), which is related to the build-up of adhesive layers. Tool wear is a dynamic process of build-up and fracture which explains the non-stable COF during the test series. Material 2 and 5 has a relatively high COF, while they both possess a completely different amount of coating porosity. Therefore, no clear relation is observed between the coating porosity and the COF.
Longer time in the furnace (yellow curve Figure 7a) results in very high COF’s for the first five samples however after running in the COF’s are comparable, most likely due to build-up of galling on the tooling which results in similar contact situation.

![Figure 7.](image)

**Figure 7.** (a) COF versus sample number and (b) COF value (25 samples) long = material 3 with long furnace time.

### 3.4. Influence of coating porosity on tool wear

The tools contain severe galling after 25 repetitions for all materials, however a large difference occurs between the materials. Material 1 to 3 have relatively low maximum galling heights (see Figure 8). The maximum heights measured for materials 4 and 5 are significantly higher, namely 38 µm and 45 µm. Materials 4 and 5 also have significantly higher amount of coating porosity. Both adhesive and abrasive wear is observed on the tools, however the main wear mechanism is adhesive wear. Asperity crushing generates debris which plays a role in compaction galling on the tool which leads to two and three body abrasive wear [8]. Materials with a lower porosity produce a lower amount of tool wear. This is in line with expectations since a higher coating porosity results in more fracture and therefore more debris which can be compacted on the tool.

![Figure 8.](image)

**Figure 8.** Line roughness measurement bottom tool line a.

Longer furnace time increased the amount of porosity in the coating and changed the phase distribution. A long furnace time results in higher visible amount of abrasive wear and a lower amount of galling (see Figure 9d), while the porosity is higher. With a longer furnace time more Al
diffuses into austenite. Therefore another aspect, most likely the type of intermetallic, is also very important with respect to wear on the tooling. The higher amount of visible abrasive wear is remarkable since a higher amount of the ‘softer’ intermetallic AlFe is present. However abrasive and adhesive wear are very dynamic processes. It is possible that for the other materials abrasive wear is covered by adhesive wear, which makes the comparison difficult. It is also possible that adhesive wear ‘protects’ the tool surface against further abrasive wear.

![Materials Images](a) Material 1  
(b) Material 3  
(c) Material 5  
(d) Material 3 28 min

**Figure 9.** Confocal measurement of bottom tool after 25 samples for several materials.

4. Discussion

High temperature friction tests are performed on the hot strip draw tester to investigate the effect of porosity in the coating on friction and tool wear. No relationship is observed between the friction and amount of porosity. However, the results of these investigations indicate that the porosity in the coating has a negative effect on galling. However, in a hot friction draw test no deformation is present. It could be that differences observed in galling in a hot friction draw test are more discriminating than in the hot pressed part. Deformation causes even more fracture of the coating. The relevance of the fracture due to the amount of coating porosity directly underneath the surface is unknown. It is therefore highly recommended to investigate the influence of coating porosity on wear with a hot pressed part.

Besides the porosity, the surface topography is also different for the tested materials. A higher surface roughness could also result in a higher amount of fractured particles. It is therefore difficult to draw hard conclusions on the influence of voids on the tool wear. The results mentioned in this paper only indicate that coating porosity negatively affects tool wear.

Wear is pressure dependent and in a hot stamping part a large range of pressures occurs depending on the position of the part. In this investigation only one pressure is investigated, which is relatively low for some radii and edges. It would be interesting to perform tests at higher pressures, if necessary with another test set up.

Highly interesting is that the amount of galling is relatively low while the porosity is high for a longer furnace time. This shows that the type of intermetallic and distribution is very important with respect to tool wear. With a longer furnace time more Al has diffused into austenite. Windmann et al. [2,24] recognised the importance of the type of intermetallics on wear. The authors published the idea to accelerate the transformation of AlSi coatings into the more ductile phase of type AlFe during austenitization, thus avoiding crack initiation and propagation in the coating during press-hardening to reduce tool wear [24]. In another article, Windmann et al. [2] showed that the abrasive wear of the tool steel surface could be decreased by adapting the phase composition in the Al-base coating. However the authors conclude that adhesive wear cannot be prevented by an adaption of the phase composition in the coating since both phases (AlFe and Al5Fe2) lead to adhesive wear of the tool steel surfaces. It could be true that adhesive wear cannot be prevented by an adaption of the phase composition in the coating as stated by Windmann et al [2]. However, it is imaginable that the amount of compaction galling can be reduced by a phase composition with higher fracture toughness due to less amount of fractured particles and/or lower adhesive strengths of different intermetallics. No information is available on the adhesive strengths for the several phases.
5. Conclusions

High temperature friction tests are performed on the hot strip draw tester to investigate the effect of porosity in the coating on friction and tool wear. Five materials with different coating porosity are investigated. The friction and wear mechanisms are similar for all materials. The friction mechanism is flattening, fracture and ploughing of adhesive tool wear through the sheet coating. The main wear mechanism is galling, however also abrasive wear is observed.

No relation is observed between friction and the coating porosity. This investigation indicates that the porosity in the coating has a negative effect on galling. The type of intermetallic and distributions is very important with respect to wear on the tooling.

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