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Influence of microstructural evolution of Al-Si coated UHSS on its tribological behaviour against tool steel at elevated temperatures

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ABSTRACT

The usage of the hot stamping process is of great importance due to the high demands for production of ultra-high strength steels (UHSS). An Al-Si coating is normally applied to the steel to prevent decarburisation and scaling during heating and to improve the corrosion resistance of the final component. During heating, the Al and the Si from the coating combine with the Fe from the steel substrate to form hard intermetallic phases. Little is known about the influence of the heating conditions on the tribological behaviour of the Al-Si coating during interaction with tool steels. The present work investigated different heat treatment parameters and the influence they had on the microstructure of the coating and the galling behaviour. With low alloying temperatures (700 °C), severe galling occurred and increasing the alloying temperature to 900 °C resulted in almost negligible material transfer. The reduction in galling was associated to the development of Fe_2Al_5 and $FeAl_2$ at the surface.

1. Introduction

In the hot stamping process an Al-Si coating is commonly applied on the ultra-high strength steel (UHSS) sheets. This coating gives good corrosion protection and has good paintability and weldability as has been reported by Suehiro et al. (2003) in their studies.

The Fe-Al-Si system is known for its complexity as it can form an extensive amount of phases that are stable at various ranges of temperatures and composition as highlighted in different studies. Krendelsberger et al. (2007) studied this system and the challenge involved for the analysis and identification of different phases as temperature increases through power diffraction, nonetheless, they were able to confirm the existence of different ternary phases reported in the open literature as well as the invariant temperatures of the reactions. Gupta (2003) carried out an analysis of the Al-Fe-Si system with the aim of confirming which phases can be encountered at different temperatures. Gupta was able to confirm the existence of nine intermetallic phases despite the small differences in chemical composition. In a later study, Maitra and Gupta (2003) found that the binary phases (Fe-Al) form solid layers. They also stated that ternary phases such as τ_1 and τ_5 can crystallise directly from liquid during cooling or by the occurrence of invariant reactions.

In the case of the Al-Si coated UHSS in the hot stamping process, when exposed to high temperatures, the Al-Si coating undergoes microstructural changes due to the formation of intermetallics as highlighted by Fan and De Cooman (2012) in their review. These intermetallic phases have also been observed and studied by other authors; Hardell et al. (2010) pointed out the formation of such intermetallic layers and the morphological changes that it causes on the surface of the coating. This was also confirmed by Borsetto et al. (2009) as they observed that increasing the holding time affects the chemical distribution of the constituents through the coating as well as the morphology of the surface. These changes in the chemistry of the coating are related to the formation of intermetallic phases, these intermetallics are formed by inter-diffusion of Al, Si and the Fe from the steel substrate. When exposed to high temperature (over 577 °C), the Al-Si coating melts. This allows the Fe from the substrate to diffuse quickly through the coating towards the surface. The increased concentration of Fe in the coating causes the formation of intermetallic phases and the coating solidifies. As the intermetallics are formed, hardness of the coating is increased and the coating becomes brittle. A multi layered structure after exposure to elevated temperatures has been observed by Grigorieva et al. (2011). They reported up to five layers (i.e. phases) that can be found within the Al-Si coating; however, this number is reduced with increased temperature and time. Furthermore, in the study by Suehiro et al. (2003), it was stated that if enough time and temperature is given, the coating homogenises into a single layer.

Veit et al. (2011) showed that even with the use of fast heating process, the multi-layered structure of the coating is still formed.

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As mentioned before, the changes of the coating at high temperatures are not limited to the phase transformations; morphological changes of the surface have also been reported in the studies done by Hardell et al. (2010) in the form of nodules at the surface after exposure to high temperature and also an increase in the average surface roughness. Borsetto et al. (2009) also observed the increased roughness of heated specimens and also showed that with long holding times, the roughness continues to increase. Veit et al. (2011) suggested that the formation of such nodules is caused by the melting of the unalloyed Al situated at the outermost layer of the coating.

Several authors have addressed the tribological behaviour of the Al-Si coated UHSS and reported occurrence of material transfer when it interacts with different tool steels with and without coatings. The wear behaviour of tool steels with and without coatings sliding against Al-Si coated UHSS has been investigated by Kondratiuk and Kuhn (2011) and found that severe adhesive wear can occur when coatings such as AlCrN or TiAlN are used. Azushima et al. (2012) observed that under lubricated conditions friction can be controlled to a steady level and suggests that wear can be reduced. Pelcastre et al. (2012) studied the occurrence of material transfer or galling on the tool steel surface and concluded that wear fragments coming from the Al-Si coated UHSS accumulate within surface defects or valleys of the surface of the tool and generate material built up. The occurrence of adhesion was also observed by Pelcastre et al. in untreated tool steels (2011); however, this adhesive tendency was magnified when certain PVD coatings were used (Pelcastre et al., 2013), however, the use of oxidised plasma nitrided tool steel reduced considerably the occurrence of galling. Hou et al. (2010) observed that die corners are sites where severe material transfer occurs and suggested that this was due to the increased contact pressure and temperature at these regions.

It is clear that the heating conditions have a significant effect on the resulting microstructure and morphology of the coating, but equally important is the fact that the existing phases also affect the tribological response. The effect of the changes of surface roughness of the Al-Si coating has not yet been thoroughly studied and its impact on galling or friction is not well understood. It has been observed that the temperature, to which the coating is exposed to, has an effect on material transfer and friction. For instance, in a study by Kondratiuk and Kuhn (2011), they suggested that at temperatures around 920 °C material transfer was reduced compared to lower temperatures when Al-Si was sliding against tool steel. In the study done by Borsetto et al. (2009) the authors observed a reduced coefficient of friction between the Al-Si coating and a hardened hot work tool steel at 700 °C in a pin-on-disc configuration. However, it is not yet clear the reason for the above mentioned cases.

In the actual forming process, the coating undergoes heating during the austenitisation of the steel (~930 °C). Upon exiting the furnace, the work-piece cools down to around 750 °C before it gets into contact with the forming tools. Even though it is acknowledged that the heating history of the coating has an influence on the tribological response, the correlation between the microstructure of the coating and the tribological response still lacks understanding.

In this work, two temperatures (700 °C and 900 °C) were chosen for the investigations with a given soaking time for alloying of the coating. From a fundamental point of view, the selected temperatures allow the formation and evolution of typical phases encountered in the forming process and others that are not often seen in the process but that are also typical in the Al-Si-Fe system. Even though the microstructural evolution of the Al-Si-Fe system has been studied, as described in the review done by Fan and De Cooman (2012), there is still lack of understanding concerning the tribological behaviour of most of the phases that form in this system, and in the particular case, in the Al-Si coated UHSS.

Table 1
Test conditions to analyse influence of alloying time.

Temperature (°C)	Soaking time (min)		
700	0	4	20
900	0	4	20

In the forming industry, there is always a drive to modify the heating conditions to increase productivity and reduce costs. However, little information is available concerning possible effects that may occur as a result of the microstructural evolution of the Al-Si coating.

This work aims to increase the understanding of the tribological behaviour of Al-Si coated UHSS under different heating conditions. Particular focus is given to the friction behaviour and galling mechanisms. Furthermore, the effect of the surface roughness of the Al-Si coating on the tribological behaviour is also studied.

2. Materials and experimental methodology

2.1. Test materials and specimens

The specimens used for the tribological tests were an upper pin of Ø2 mm made from a hot work, quenched and tempered tool steel. A similar composition is normally used for tools in the actual hot stamping process. The tool steel pin surface was polished to an Sa value of ~50 nm. The lower disc (Ø16 mm and 1.7 mm height) was made from Al-Si-coated UHSS which was welded onto a steel backing plate of Ø24 mm and 6.3 mm height. The Al-Si coated steel is widely used as workpiece in the hot stamping process. According to the review done by Fan and De Cooman (2012), the boron steel is usually aluminised by hot dipping into a molten Al alloy bath with a composition of approximately 88% Al, 9% Si and 3% Fe in weight percentage.

2.2. Heat treatment of the Al-Si coated boron steel

Initially, the effect of temperature on the evolution of the Al-Si coating microstructure was considered.

For this study, three different soaking times were used for the analysis of the microstructural evolution. Table 1 shows the times used for each temperature. A soaking time of 0 min means that the samples were heated up to the desired temperature and then cooled down immediately. The coating undergoes melting when exposed to temperatures higher than 570 °C followed by solidification caused by diffusion and interaction between the constituents of the steel substrate and the Al-Si coating. The 0 min soaking time was selected to determine whether the presence of melted coating material could be observed and its effect on the tribological response. A soaking time of 4 min was selected as it is close to the duration normally used in the hot stamping process. In the study done by Suehiro et al. (2003), it was proposed that given enough time and temperature, the coating can develop a structure with a single layer. The soaking time corresponding to 20 min was selected to evaluate changes in the microstructure of the Al-Si coating (shifts in the formed layers) and the effects on the tribological behaviour.

A schematic of the heat treatment history is shown in Fig. 1. The heat treatment was performed in the tribometer itself to have the same heating conditions that are normally obtained during the tribological tests.

2.3. Tribological tests

Tribological tests were carried out using an Optimol SRV high-temperature reciprocating friction and wear tester. Before the tests, all specimens were cleaned with ethanol and dried. The upper pin