Coating effects on the galling behaviour of aluminium metal forming processes

Xiao Yang¹, Yiran Hu¹, Yang Zheng¹, Denis J. Politis¹, Liliang Wang¹*

¹Department of Mechanical Engineering, Imperial College London, London SW7 2AZ, UK

liliang.wang@imperial.ac.uk

Abstract. This paper investigates the effect of coatings on the galling behaviour in metal forming processes. To investigate this phenomenon, pin-on-disc tests were conducted on the Anton Paar THT tribometer with discs manufactured from tool materials and pins manufactured from aluminium to represent the workpiece. Three different coating conditions were tested: uncoated contact, AlCrN and CrN coatings, at three different temperatures: room temperature, 300°C and 450°C. The investigation indicated that advanced coatings have a significant effect on coefficient of friction and galling behaviour, while these effects may rely on the selection of substrate and forming temperature. In general, compared with uncoated contact conditions, lower friction coefficients were generated with coated tools. In addition, the selection of aluminium grade for the pin affected friction coefficient, with AA6082 generating higher friction coefficients compared to AA7075.

1. Introduction

Aluminium sheet metal forming processes have been widely adopted in the automotive and aviation industry for the purpose of producing lightweight components. However, galling, an adhesive wear mechanism resulting in an aluminium transfer layer accumulating on the counter-part tool material, is always observed during sheet metal forming processes, which limits the quality of formed surfaces and reduces tool-life [1, 2]. There are various methods to reduce the tendency of galling generation [3-5]. Surface roughness has a large effect on galling, which means that low surface roughness would extend the crucial sliding distance before galling is initiated [6]. In addition, advanced coatings may also provide resistance to galling [7]. Previous investigations into the galling phenomenon have largely focused on the tribological evaluations of coating materials at room temperature. Thus it is of great interest to observe the behavior of coatings at elevated temperatures and also the effect of substrates and pin materials on coatings behavior.

In this paper, the galling behavior of a range of coatings and substrate material were investigated at a range of temperatures for two aluminium pin materials. Due to the industrially sensitive nature of the substrate tooling materials used in this study, substrate names have been replaced by the notation ‘Substrates 1, 2 and 3’.
2. Experimental setup

2.1. Coating combinations
Coated tooling materials were tested through Pin-on-Disc tests using aluminium pins made from AA6082-T6 and AA7075-T6, with a spherical head of 2.5 mm radius and disc diameter 55mm, with materials provided by Schuler Pressen GmbH, as shown in Figure 1a. The load applied in the tests was 5N. All three tooling substrates were pin-on-disc tested with the application of three coating conditions: uncoated condition, AlCrN and CrN coatings.

The coating material, substrate material, pin material and temperature were treated as independent variables of the test, with coefficient of friction and galling effect as the dependent variables.

![Pin diameter: 5 mm Disc diameter: 55 mm](image)

**Figure 1.** Schematic diagram of a) pin-on-disc experimental setup and b) Anton Paar THT tribometer

2.2. Pin-on-disc experiment
An Anton Paar THT tribometer, as shown in Figure 1b was used to conduct the pin-on-disc friction tests, and the testing conditions are listed in Table 1. In the table, the pin material and the temperature of the test for each substrate and coating are shown. The evolution in coefficient of friction was recorded and compared between different coatings.

| Substrates | Coatings | Coatings |
|------------|-----------|-----------|
| Sub1       | Uncoated  | AlCrN     | CrN       |
| Sub2       | 25/300°C  | 25/300/450°C | 25/300/450°C |
| Sub3       | 25°C      | 25°C      | 25°C      |

3. Evolutionary phenomenon of friction coefficient
In aluminium sheet metal forming processes under either lubricated or dry conditions, it is observed that the coefficient of friction increases as an aluminium transfer layer is formed on the tool surfaces. This evolutionary phenomenon shows that the coefficient of friction gradually increases until reaching a steady state value [8]. By analysing this phenomenon, the aluminium layer that is generated on the sliding interface is identified as the origin of the increasing friction coefficient.

Previous research has predominantly focused on the three main tribological responses of the adhesive wear system, namely: 1) material transfer onto the counterpart, also called galling; 2) progressive loss of material or wear; and 3) friction.

For friction conditions in adhesive wear, the coefficient of friction increases from an initial value (COF1) to a higher constant value (COF2) with the terms ‘running in state’ and ‘steady state’ widely used to describe the adhesive wear conditions from unsteadiness to stabilisation. The sliding distance required to reach stabilisation from an initial stage is defined as x, as shown in Figure 2.
Evidence of the interactions between friction, wear and the aluminium transfer layer has been presented and analysed by the third body theory [9]. In this theory, the third body is defined as the transfer layer generated as a result of the interaction between the original mating pairs (first bodies). At the beginning of the sliding process, the aluminium pin is in direct contact with the tool material and friction is generated by adhesion and ploughing between asperities of aluminium and tool. The relative motion shears the contact junctions and breaks the soft aluminium asperities, which may result in detachment of solid aluminium and formation of loose wear particles. With the combined effects of high contact pressure and shearing, surface defects and the high adhesion characteristic of aluminium, these wear particles are likely to adhere to the tool surface and form aluminium lumps, which further accumulates as an aluminium transfer layer. Transfer and back-transfer mechanism may exist between wear particles, solid aluminium and transfer lumps of aluminium. The ejection of wear particles may also be active through the entire sliding process even when the steady state is reached.

At the steady state, although wear particles are continually generated, the morphology of the interface is relatively stable and the wear particle generation and ejection mechanisms play a critical role in balancing the system. When the generation rate of wear particles equals the ejection rate of wear particles, the changing rate of the volume of transfer layer entrapped at the contact surface becomes zero which means that a dynamic steady state has been reached.

It is well observed that the aluminium transfer layer strongly affects the aluminium-tool material tribo-system. The effects include a change from tribology between solid aluminium against solid tool materials to a much more complex system including transfer layer. That is, when an aluminium transfer layer forms on the tool material surface, it partly separates the original contact between solid aluminium and tool material and presents a new physical and chemical morphology of the interface compared to the initial ‘clean’ contact.

After the aluminium transfer layer is formed, friction may be reduced since large aluminium wear particles are generated and may roll at the interface to accommodate the velocity difference between the contact couple. In addition, shearing stress may be reduced by sliding between soft aluminium instead of aluminium and tool material asperities. On the other hand, cohesion of aluminium which builds stronger metallic bonds than aluminium-tool material bonding and the increased integral surface roughness may contribute to the increase of friction. The combination of these two aspects may finally give rise to an increased value of friction coefficient at the steady state.
4. Results and discussion

![Graph showing friction coefficient and sliding distance to reach the stable stage at room temperature under uncoated and coating conditions for different substrates.]

**Figure 3.** Difference between results of uncoated and coating conditions at room temperature using AA6082 pins with regard to different substrates

As is shown in Figure 3 (x is the sliding distance in mm and same for the following figures), results of friction coefficient and sliding distance to reach the stable stage at room temperature under uncoated and coating conditions are compared with regard to a) substrate 1, b) substrate 2 and c) substrate 3. From the comparison, substrates on which coatings are applied may have effects on the performance of different coatings. In terms of substrates 1 and 2, there is little difference between uncoated and coating conditions. Whereas at the condition of substrate 3, appliance of coatings caused the value of COF2 to decrease approximately 45% when compared with that of uncoated condition. This difference caused by substrates may be given rise to the interaction between work-piece and substrates. Although coatings were applied onto the substrates, there may be areas of the substrate that came in contact with the work-piece due to small thickness of the coatings.
Figure 4. Difference between results of uncoated and coating conditions of substrate 1 using AA6082 pins with regard to different temperatures

Temperature may also influence the performance of coatings. As shown in Figure 4, application of coatings demonstrates little advantage in terms of friction coefficient over the uncoated surface at room temperature with substrate 1. However, the values of COF2 under uncoated condition decreased by approximately 40% with coatings applied at 300°C. This behaviour between different temperatures was also observed in substrate 2, as shown in Figure 5.

Figure 5. Difference between results of uncoated and coating conditions of substrate 2 using AA6082 pins with regard to different temperatures
Figure 6. Temperature effects on friction coefficient results at coating conditions with AA6082 pins

When results of the same substrate and coating type but at different temperatures are compared, as shown in Figure 6, temperature effects on friction coefficient can be investigated. In general, both values of COF1 and COF2 increased with the increasing temperature for AlCrN and CrN coatings. However, the coating types may affect the extent to which COF2 was increased. For AlCrN, the increase of temperature from room temperature to 450°C would cause the value of COF2 to increase approximately 114%; while for CrN, the increase was only 53%. The increase of friction coefficient may result from the following reasons: 1) the softening of coatings at high temperatures could lead to a larger contact area on the interface thus higher friction coefficient; 2) high temperature which results in more active atomic motions may generate larger adhesion forces between work-piece and tool [10].

Figure 7. Effects of pin material on COF2 at coating conditions with regard to different temperatures
Figure 7 shows the comparison between results of COF2 in the friction tests with different pin materials, AA6082 and AA7075 respectively. At room temperature, the difference was small for both AlCrN and CrN coatings, although the value of COF2 using AA6082 pins was slightly greater than AA7075 pins. At 450°C, a large difference was observed and AA6082 pins generated significantly greater COF2 for both coatings. This phenomenon may be caused by the higher hardness of AA7075, which can lead to low wear rate. In addition, as is shown in Fig. 5, the effects of pin material are related to temperature and coating types.

5. Conclusion
In general, advanced coatings have significant effects on anti-galling performance and coefficient of friction. However, these effects may rely on a suitable selection of substrate, temperature and the corresponding work-piece material. It is clear that the severity of galling has a close relationship with the value of friction coefficient, and it can be observed that they both increase with the increase of temperature from the experimental results. The benefit of advanced coatings is more obvious at elevated temperatures for substrate 1 and 2. For the same coating conditions, AA7075 pin material may generate a lower coefficient of friction and this difference will become larger with the increase of temperature.

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