Friction Characterization of Al-Si Coated Ultra-High Strength Steel under Hot Stamping Conditions

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Abstract. Friction characterization of a hot stamped 1,800 MPa Al-Si coated ultra-high-strength steel (UHSS) is considered. Quantification of the coefficient of friction during a hot stamping process is essential for an accurate constitutive finite element model. The current work considers the twist compression test (TCT), in which an annular cup rotates against the surface of a fixed specimen using heated tooling. The measured sliding force and normal force determine the coefficient of friction. The test conditions used in this research simulate thermo-mechanical histories operative during hot stamping. Specimens are austenitized in a chamber furnace at a nominal temperature of 930 °C and a hold time of 5 minutes. They are then transferred to the TCT apparatus in which frictional sliding and die quenching occur simultaneously. The tooling components are uncoated and heated to 80 °C. Contact pressure of up to 30 MPa was considered between the tooling and specimen and a sliding speed of up to 38 mm/s. An increase in contact pressure caused the coefficient of friction to increase during dynamic friction. On the other hand, changes in sliding speed did not have a significant impact on the coefficient of friction. Likewise, repeated tests on the same tooling surface show that the coefficient of friction remains consistent during tool wear. Surface roughness of the tooling only increased after the first test and then remains stable during subsequent tests.

1. Introduction
Vehicle weight reduction can be achieved through materials that offer superior strength/mass ratio than those of their predecessors. PHS1800 is an ultra-high-strength steel (UHSS) that features a rated tensile strength of around 1,800 MPa following hot stamping. Due to its higher tensile strength compared to current hot stamped grades (1,500 MPa), PHS1800 provides superior crash protection for components such as bumper beams, B-pillars, and door rings [1]. PHS1800 achieves its high tensile strength through hot stamping, in which austenitized and malleable material is formed into its desired shape while die quenching to obtain a martensitic microstructure. The PHS1800 analyzed in this paper is coated with Al-Si at a concentration of 150 g/m². In order to support accurate simulation of the hot stamping of this material, its friction characteristics must be accurately determined [2].
Hardell et al. [3] determined that sliding speed has a marginal effect on CoF for boron steel, while an increase in contact pressure leads to a decrease in CoF. Due to the high temperature of the blank in hot stamping, lubricant is not usually applied prior to forming. Therefore, asperities on the tooling surface and blank are in direct contact without any lubricant separation. The friction mechanisms involved are mainly adhesion and ploughing according to Hardell et al. [4]. The characteristics of adhesion are affected by the interfacial shear strengths of the materials, their real contact area, and their hardness values. Ploughing is determined by the surface roughness of the blank and its tooling. For Al-Si coated boron steel, Hardell et al. [4] found that abrasion as well as adhesion are the main friction mechanisms. Venema et al. [5] determined that the CoF is dependent on the blank temperature. Yanagida et al. [6] also found that the mean CoF increases with increasing temperature. The main friction mechanism changes from abrasive wear between 650 and 750 °C to adhesive wear below 600 °C [5]. This dependence becomes less sensitive when layers of adhered material are build-up on the tooling surface [5].

Although initial tooling surface conditions affect the coefficient of friction (CoF), the CoF becomes constant after an initial running-in for untreated tooling surface [4]. This stabilization of the CoF is caused by material transfer from the Al-Si coating to the tooling surface, which maintains a consistent surface profile through wear [4]. The tooling surface can also transfer its constituents to the Al-Si coating and create a layer of oxidized wear debris above the coating according to Pelcastre et al. [7]. This protective layer reduces material transfer by decreasing tooling surface contact with the Al-Si coating underneath.

Various tribological test methods have been used to characterize the friction of UHSS in hot stamping, such as the pin-on-disk test, in which a cylindrical pin made of hot work tooling material contacts a flat rotating disk made of UHSS [7]. Although contact conditions in pin-on-disk tests can be easily modified, they deviate from those in a hot stamping process, because the contact surface is small and can cause excessive ploughing at the contact point due to material build-up in front of the pin [8]. A tribosimulator apparatus for flat drawing developed by Yanagida et al. [6] has also been used to replicate friction conditions in hot stamping. A pair of flat clamps made of hot work tooling material contact a strip of UHSS, which is pulled through the clamps at a constant speed. As the continuous UHSS strip exits the austenitization furnace, it directly enters the pair of clamps. The study has shown that water-based lubricants sprayed on the tooling surface can significantly decrease the CoF under hot stamping conditions [6].

The current study uses the twist compression test (TCT) developed by Schey et al. [9] to replicate hot stamping friction conditions. Friction parameters such as contact pressure, sliding speed, and sliding distance are varied to evaluate their impact on CoF.

2. Experimental Methods
2.1. Test Apparatus
The TCT method involves a heated friction cup rotating against the surface of a stationary test specimen, which is supported by a gimballed and heated specimen holder as shown in Figure 1a [10]. The friction cup is made of Uddeholm Dievar tool steel hardened to 53 HRC, which is used for hot stamping tooling. Its contact surface features a concentric profile shown in Figure 1b. Since the friction motion is circular and parallel, the measured CoF is independent of sheet rolling direction.

Cartridge heaters and embedded thermocouples can maintain the friction cup and specimen holder at a constant temperature. Both are heated to the expected hot stamping tooling temperature prior to forming, which was taken as 80 °C for this study. Nominal contact pressures are 5, 15, 25, and 30 MPa. Nominal sliding speeds are 10, 20, 30, and 38 mm/s. A total sliding distance of 100 mm is maintained for all tests.

Cup rotation starts immediately upon contact with the specimen. To prevent overshooting the nominal contact pressure, the applied contact pressure increases linearly to its nominal value over a sliding distance of 10 mm.
A load cell installed under the specimen holder measures contact pressure according to the friction cup’s contact surface area. Another load cell installed on a torque arm of the specimen holder prevents the holder from rotating and measures CoF according to the Coulomb model of friction through equation 1. $F_f$ is friction force; $N$ is applied normal force from the specimen holder; $T$ is reaction torque from the specimen holder due to friction; $r_m$ is the medium cup radius; $F_a$ is measured reaction force from the torque arm of the specimen holder; $r_a$ is the radius formed between the torque arm’s load cell and the center of rotation.

$$\text{CoF} = \frac{F_f}{N} = \frac{T}{r_m N} = \frac{F_a r_a}{r_m N} \quad (1)$$

### 2.2. Test Procedure

Prior to testing, all friction cups and PHS1800 specimens are cleaned in soapy water, rinsed with acetone, and dried with a paper towel to remove surface contaminants. As shown in Figure 2, the TCT process starts with heating of the specimen in a Carbolite chamber furnace at a nominal temperature of 930 °C and a hold time of 5 minutes to allow full austenitization. Then, the specimen is manually transferred from the furnace to the specimen holder of the TCT apparatus. The transfer occurs over a period of approximately 10 seconds until the specimen contacts the friction cup. As soon as the specimen contacts the friction cup, the latter begins to rotate while contact pressure increases to its nominal value. After each test, the worn specimen and friction cup are replaced with a new set prevent excessive wear on the same surface. Each set of test conditions involves five repeats for statistical significance.

![Figure 2](image.png)

**Figure 2.** TCT test process begins with austenitization of the specimen at 930 °C for 5 minutes. The specimen is then manually transferred from the furnace to the specimen holder of the TCT apparatus. The transfer occurs over a period of approximately 10 seconds until the specimen contacts the friction cup. As soon as the specimen contacts the friction cup, the latter begins to rotate while contact pressure increases to its nominal value. After each test, the worn specimen and friction cup are replaced with a new set prevent excessive wear on the same surface. Each set of test conditions involves five repeats for statistical significance.
Experiments were also performed to examine the effect of tool wear on CoF. In this set of experiments, only the sheet specimen is replaced after each test while the same friction cup is used for ten consecutive tests. Five sets of tool wear sequences using five different friction cups were completed to obtain statistically significant data (a total of 50 friction tests). These experiments utilized a relatively high contact pressure of 30 MPa in order to promote higher levels of wear.

2.3. Surface Roughness Measurement
To determine the impact of tool wear on surface roughness of the friction cup, the concentric contact area of each friction cup is measured at five different locations using a Taylor-Hobson contact profilometer. The precision of the contact profilometer is 0.02 μm Ra. The cutoff length (Lc) is set to 0.25 mm.

Surface profiles of the specimens are taken with a Keyence optical profilometer. Surface roughness measurements obtained using the contact profilometer comply with those taken with the optical profilometer.

3. Results and Discussion
3.1. Initial Surface Roughness
Prior to austenitization, the Al-Si coated PHS1800 specimens have a metallic surface finish in their as-delivered condition as shown in Figure 3a. After heat treatment through austenitization and die quenching, the surface becomes matte in color, as shown in Figure 3b. The average surface roughness increases during austenitization from 1.26 to 2.76 μm Ra, as shown in Table 1. Wear marks appear on each specimen after friction and indicate that the Al-Si coating is gouged by the cup during rotation as shown in Figure 3c.

![Figure 3. Al-Si coated PHS1800 specimen in various stages of testing: (a) As-delivered. (b) After heat treatment. (c) After friction.](image-url)

|                | Before Heat Treatment (Ra) | After Heat Treatment (Ra) |
|----------------|---------------------------|---------------------------|
| Average        | 1.26 μm                   | 2.76 μm                   |
| Std. dev.      | 0.08 μm                   | 0.34 μm                   |
| Difference     | 1.50 μm                   |                           |

3.2. Impact of Sliding Speed on Coefficient of Friction
Figure 4 represents a typical CoF versus sliding distance curve generated by a TCT test. The CoF is initially high due to static friction and then rapidly decreases as it transitions to dynamic friction. Following this initial drop, the CoF gradually increases as the cup continues to rotate. The CoF does not reach a steady state, because the specimen temperature is continuously decreasing due to heat conduction from the hot blank to the tooling and specimen holder, as well as convection to ambient air [5]. The contact pressure reaches its nominal value after a sliding distance of 10 mm.
Figure 4. Typical CoF and contact pressure curves obtained from TCT test on Al-Si coated PHS1800.
Nominal sliding speed: 20 mm/s. Nominal contact pressure: 30 MPa.

CoF was characterized at sliding speeds from 10 to 38 mm/s using a contact pressure of 15 MPa. Figure 5a shows the CoF versus sliding distance response for each sliding speed at a sampling interval of 10 mm sliding distance. Each CoF data point is an average over a sliding distance of 10 mm to filter out noise. For example, the CoF value at the sliding distance position of 20 mm is an average CoF from 15 to 25 mm sliding distance. For the CoF data points at 100 mm, the average is computed over 5 mm. The CoF data in Figure 5a varies with sliding distance, as discussed above, but shows similar behavior for all sliding speeds considered. An average CoF was calculated as the average value over a sliding distance range of 10-100 mm; this range was adopted to avoid the initial transients below 10 mm sliding distance. The average CoF is plotted as a function of sliding speed in Figure 5b. In general, there is very little dependence of CoF on sliding speed at 15 MPa contact pressure and the range of speeds considered, as demonstrated by the overlap of the confidence intervals in Figure 5b.

Figure 5. (a) CoF of PHS1800 at sliding speeds from 10 to 38 mm/s. Contact pressure is maintained at 15 MPa. Each data point corresponds to an average CoF over a sliding distance of 10 mm. (b) Average CoF (10-100 mm sliding distance) at each sliding speed with a common contact pressure of 15 MPa. Error bars correspond to 95% confidence interval.

3.3. Impact of Contact Pressure on Coefficient of Friction
Samples were also tested using contact pressures in the range 5-30 MPa at a sliding speed of 20 mm/s. Similar to Figure 5a, Figure 6a shows the CoF versus sliding distance response for each contact pressure
at a sampling interval of 10 mm sliding distance, in order to filter out noise. Also plotted is the average CoF over a sliding distance of 10-100 mm as a function of contact pressure (Figure 6b). In contrast to the lack of dependency on sliding speed (Figure 5a), the CoF does exhibit a dependency on contact pressure beyond the scatter present in the data, as seen in Figure 6a and b. The increase in average CoF with contact pressure (Figure 6b) is almost linear over a range of contact pressure from 5 to 25 MPa. Much of the contact pressure dependence can be attributed to asperity flattening within the contact interface. The asperity flattening leads to a larger contact area, thus a higher CoF [5]. Interestingly, Hardell et al. [3] reported a decrease in CoF with contact pressure in contrast with the current work, however, those tests considered self-mated boron steel (essentially sliding on itself), tested at room temperature. Above this pressure range, the CoF did not change relative to that at 25 MPa. The strongest dependency on contact pressure is seen over a sliding distance of 10 to 60 mm (Figure 6a). Beyond this range, the CoF curves appear to saturate and converge.

3.4. Impact of Tool Wear on Coefficient of Friction

In hot stamping production operations, the tooling serves to hot stamp many thousands of parts before repair or replacement due to wear. In order to examine the effect of repeated frictional sliding on the same tooling surface, Figure 7a shows the results from repeated tests performed using fresh sheet samples on the same friction cup. The results demonstrate that repeated use of the same friction cup for up to 10 TCT tests did not significantly change the average CoF beyond the initial transients prior to 10 mm sliding distance. Each test corresponds to a sliding distance of 100 mm, thus totaling a sliding distance of 1 m after 10 TCT tests on the same friction cup. Figure 7b does not show any statistically significant trend in CoF since most of the 95% confidence intervals overlap among the data points. As a result, tool wear in the early stages of hot stamping production runs should not result in significant impact on its friction characteristics. Wear over the longer term requires further investigation.
Figure 7. (a) CoF of PHS1800 at a constant contact pressure of 30 MPa and a sliding speed of 20 mm/s. A total of 10 TCT tests were performed on each friction cup with a sliding distance of 100 mm/run. Each curve (R1-R10) corresponds to success repeat tests on the same friction cup. (b) Average CoF (10-100 mm sliding distance) for each TCT repeat test. Error bars correspond to 95% confidence interval for each repeat test.

3.5. Surface Roughness of Friction Cups and Worn Specimens

Figure 8. Average surface roughness of friction cup (tooling) in lapped condition and after each TCT repeat test. Measurements are taken in directions parallel and perpendicular to the sliding direction against the specimen. Error bars correspond to 95% confidence interval for each TCT run.

Prior to the first tool wear test, the friction cups were lapped to a uniform, isotropic surface finish to represent a new tooling condition. After the first test, the surface roughness of the cup significantly increases for measurements taken directions parallel and perpendicular to the sliding direction, as shown in Figure 8. The Ra value determines surface roughness in this study. It corresponds to the arithmetic average distance from the profile’s peaks and valleys to the mean profile height. Interestingly, surface roughness remained consistent after all subsequent TCT tests on the same friction cup. This supports the previous observation that tool wear does not have a statistically significant impact on CoF, at least for the limited number of repeat tests performed here.

Figure 9. Average surface roughness of wear marks on single TCT test specimens using new friction cups with (a) sliding speeds from 10 to 38 mm/s at 15 MPa. (b) Contact pressures from 5 to 30 MPa at 20 mm/s.
After single TCT tests using new friction cups with sliding speeds from 10 to 38 mm/s, the wear marks on the specimen surface show a decrease in average surface roughness in the direction perpendicular to the sliding direction as sliding speed (Figure 9a) or contact pressure (Figure 9b) increases. The average surface roughness in the direction parallel to the sliding direction decreases from 10 to 20 mm/s then remains consistent at higher speeds. The surface roughness in the direction parallel to the sliding direction decreases as pressure increases from 5 to 15 MPa, but then remains consistent at higher contact pressures. The decrease in surface roughness is likely caused by an increasing amount of rough Al-Si coating ground away by the friction cup. However, the statistical significance of the observed trends is low due to large overlapping 95% confidence intervals.

4. Conclusion
The friction characteristics between PHS1800, an Al-Si coated ultra-high-strength steel with tensile strength rated at 1,800 MPa, and uncoated Uddeholm Dievar tool steel were evaluated in twist compression tests (TCT) under hot stamping conditions. The averaged CoF curves can be implemented into a finite element analysis code, for example, for hot stamping simulation. The following conclusions can be drawn from the current experiments.
1. The CoF did not show a strong dependency on sliding speed for the range of conditions considered.
2. The CoF increased with contact pressure over range 5-25 MPa, but appeared to saturate beyond this level.
3. The surface roughness and CoF in repeat testing using the same friction cup did not appear to change significantly after the first test.

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