Investigation of frictional behavior of steel and aluminum at different temperatures

G Huang, F Fenton
ArcelorMittal Global R&D, East Chicago, IN 46321 USA
gang.huang@arcelormittal.com

Abstract. In order to evaluate the performance of the press line, it is essential to investigate the frictional behavior and properties of materials under production temperatures. In servo press line production conditions, the tooling temperature can reach 45-55 °C after around 150 stampings. In this investigation, a clamping fixture with drawbead and flat plate inserts was employed to conduct the friction tests at room temperature and an elevated temperature (54 °C). Three mild steels and two aluminum grades (5000 and 6000 series) were used in the tests. The results from drawbead tests showed that friction force on the two aluminum materials increased by 10% at 54 °C compared to that at room temperature. However, for the 3 steels the change of friction force was negligible from 22 °C to 54 °C. This implies that for exposed panel applications, the selected steel grades might have a more controlled sliding behavior potentially resulting in better control of formability than aluminum grades for the range of temperatures observed during production stamping.

1. Introduction

Cold stamping has been widely applied by a variety of manufacturing industries to form metal parts of different shapes. After workpieces are pushed into a die cavity for flowing through drawbead during a stamping process, they can experience relative movement at the metal/tooling interface that will be impacted by the tribological behavior, which together with the dissipated energy from the plastic deformation of the parts can lead to appreciable increase of temperature of the dies. Therefore, the cold stamping might not stay cold after many stamping strokes. Accordingly, metal flow control is an important aspect of stamping process optimization as it is essential to assure part quality.

Several tests are used in the stamping industry to determine the frictional behavior of the sheet metal, such as the drawbead simulator (DBS) test [1], bending under tension (BUT) test [2], and a simple flat plate sliding test to determine the frictional behavior typically characterized by a constant friction coefficient as in the Coulomb’s model. These tests were designed to simulate the material experiencing friction at different locations of the stamping die. While frictional behavior of metals at temperature higher than 200 °C during warm forming has been extensively studied experimentally or numerically [3-5], there are very few investigations on the frictional behavior for steel and aluminum at a moderately elevated tooling temperature during cold stamping. Since temperature might have different effect on friction for steel and aluminum, the control of formability is important to manufacturer to ensure the outcome quality of cold stampings.
In this study, the frictional behavior using drawbead and flat binder (strip drawing) tests was characterized for different mild steel and aluminum grades at different temperatures. The friction performance was compared between steel and aluminum through studying the frictional behavior at room and elevated temperature.

2. Experimental method

2.1. Materials

Three mild steels with same thickness and two aluminum grades with different thicknesses were used in the friction tests. The two Extra Deep Draw Steel (EDDS) materials have very similar mechanical properties, except that EDDS-2 has a pre-phosphate layer on the Galvanealed (GA) coating. The mechanical properties of the four materials were listed in Table 1.

| Material | Coating | Thickness (mm) | YS (MPa) | TS (MPa) | TEL (%) |
|----------|---------|----------------|----------|----------|--------|
| EDDS-1   | GA      | 0.63           | 162      | 313      | 45     |
| EDDS-2   | GA (with pre-phosphate) | 0.63 | 149 | 303 | 47 |
| BH340    | GA      | 0.63           | 240      | 365      | 28     |
| Al-5xxx  | None    | 0.76           | 94       | 203      | 26.7   |
| Al-6xxx  | None    | 0.90           | 111      | 211      | 22     |

2.2. Experiment

2.2.1. Friction test with drawbead. The clamping fixture housing the drawbead insert was used to conduct the friction tests, as shown in Figure 1. The drawbead set geometries are shown in Figure 2. To achieve a stable and accurate temperature control, an electrical heating system with a new die set was developed. Two independent resistance heating units were installed in the drawbead holders (for the punch and die of the drawbead set) and were controlled separately by the control unit. Thermal Insulators made of Mica were imbedded outside the drawbead holders to minimize the heat loss, so as to reach a stabilized temperature during the test. The heating system was able to render the temperature control between 22 °C and 200 °C. In this study, room temperature (22 °C) and the elevated temperature, 54 °C, were applied in the friction tests. The testing parameters are listed in Table 2.
Specimens were cut with same dimensions of 889 mm × 101.6 mm, where the length of 889 mm is in the rolling direction. Thereafter, the edges were deburred thoroughly. No lubricant was applied on the specimen surface. Before testing, both steel and aluminum specimens were uniformly and thoroughly wiped with cloth towels to remove any surface debris, while no cleaning chemicals was applied. For tests at the elevated temperature, the punch and die of drawbead set were heated to reach the same temperature (54 °C) before starting the test. During the test, the specimen was first gripped below by the hydraulic gripping fixture which was connected to the actuator; then the top clamping fixture closed the drawbead set, followed by the pulling of the specimen through the drawbead right after the clamping load was reached. In this process, the data of pulling force, displacement and clamping load were recorded.
2.2.2. *Friction test with binder (strip drawing test).* The friction test with the flat binder is similar to the conditions using the drawbead, except that the die insert was replaced with flat plates, as shown in Figure 1b. As the specimen was in direct contact with the flat binders, no clearance was set. For the current tests, a pressure of 5 MPa was applied to the specimen. Table 2 also shows the testing parameters of the flat binder tests which were conducted on the 5 materials at room temperature and 54 °C.

| Test parameters       | Drawbead                  | Flat binder            |
|-----------------------|---------------------------|------------------------|
| Specimen size         | 101.6 mm x 889 mm         | 101.6 mm x 889 mm      |
| Testing Temperatures  | 22 °C and 54 °C           | 22 °C and 54 °C        |
| Pulling speed         | 200 mm/s                  | 200 mm/s               |
| Pulling distance      | 150 mm                    | 150 mm                 |
| Clearance             | 10%                       | 0%                     |
| Clamping pressure     | 5 MPa                     | 5 MPa                  |

3. Results and discussions

3.1. Results from drawbead friction tests

In the drawbead friction tests, the specimens were subjected to bending and unbending deformation mode when pulled through the drawbead, which results in springback. Figure 3 shows pictures of the tested specimens of EDDS1 and the 5xxx aluminum, where more severe springback was exhibited for the aluminum due to its lower modulus.

![Figure 3. Example of specimens after tests](image)

For tests at room temperature, 10% of material thickness was used for drawbead clearance by adding or removing shims. When the drawbead reached 54 °C for elevated temperature testing, it was found that the gap between the two flat blocks (at the location of drawbead and elsewhere) was reduced by about 0.08 mm, which is significant compared with the thickness of the mild steels. To study the effect of the change in clearance due to the thermal expansion from the tooling on the frictional behavior, two different types of tests were conducted: one with temperature compensation to maintain the same clearance, the other without temperature compensation or any clearance adjustment.

For the tests at 54 °C with temperature compensation, shims with thickness around 0.08 mm were used to retain the 10% of clearance. Figure 4 gives an example of comparison of pulling force on EDDS2 and Al6xxx as function of pulling distance. Other grades of steel and aluminum showed similar trend where with the maintained clearance, the friction force for 3 steels was reduced by around 10% at the elevated temperature, as compared with for room temperature, while for the two aluminum grades the friction force remained the same at the elevated temperature with the clearance adjustment.
Figure 4. Example of comparison of frictional behavior between steel and aluminum with temperature compensation for clearance

For the tests at 54 °C without temperature compensation, no adjustment for clearance was applied, even though the clearance was significantly reduced by the thermal expansion of the tooling. Figure 5 summarizes the averaged pulling force along pulling distance for the 5 materials. The trend is clear that for three mild steels, the friction force was almost the same between 22 °C and 54 °C, even though the clearance at 54 °C was much lower than at 22 °C. However, for the two aluminum grades the friction force increased by 10% at 54 °C due to the clearance shrinkage.

Figure 5. Summary of friction test results using drawbead without clearance adjustment

An example of the result of pulling force as a function of pulling distance is shown in Figure 6 for steel and aluminum. From Figures 5 and 6, it is obvious that the friction force exerted by the drawbead was not affected by the increase of the temperature when no extra adjustment was applied at the elevated temperature, which was somehow reflecting with clearance compensation for temperature the friction force of two aluminum grades increased by about 10%. This indicated that the tested steels had better control of formability in terms of friction performance than aluminum.

It should be noted that at pulling distance around 100 mm, there was a spike of friction force for the steels. This might be mostly caused by the roughening of the surface at the contact location away from
the drawbead which was induced by the closing of the drawbead. Since the tooling gap for the steels are much lower than those of the aluminum grades due the thickness difference (while the clearance of 10% is the same), the surface roughening could be more significant than for the aluminum grades.

![Figure 6. Example of comparison of frictional behavior between steel and aluminum with no temperature compensation for clearance](image)

### 3.2. Results from strip drawing friction tests with flat binder

The drawbead friction test was able to mimic the material flow through the drawbead for the stamping shop, however it could not directly lead to the determination of correlation of coefficient (COF) as the friction force was dependent on the bending and unbending moment, which was greatly influenced by the thickness of the material. Therefore, an inverse method is required to determine the COF from the drawbead friction test [6]. In contrast, the strip drawing test, which forced the specimen directly contact with the flat binder, enables the direct determination of COF using Equation (1):

$$f = \frac{F}{2N} = \frac{F}{2pS}$$  \hspace{1cm} (1)

where $f$ is the COF, $F$ the pulling force, $N$ the normal force applied on the specimen, $p$ the pressure and $S$ the contact area.

Figure 7 shows the pulling force as function of displacement for the two EDDS steels at room temperature and 54 °C. The COF calculated based on Equation (1) is summarized in Table 3. It can be seen that, in general the three mild steels have similar behavior of friction between room temperature and 54 °C, except that there was slight increase of COF for EDDS-1 (without pre-phosphate). Furthermore, the repeatability of tests was fairly high for all the tested steels. Table 3 indicated that the COF of EDDS with pre-phosphate was lower (around 10%) than that EDDS without pre-phosphate. This demonstrated that pre-phosphate has positive effect on the reduction of COF.

Figure 8 shows the pulling force as function of displacement for the two aluminum grades. Large variation was exhibited between test repeats. Meanwhile, a steady state of friction force was not reached for nearly all test repeats, as depicted in Figure 8. The highly scattered data prevented COF from being calculated for the two aluminum grades. The variability of the data was caused by the frequent breakage of aluminum specimens during the tests: splitting over 50% of the specimens was observed for both materials.
Even though the reduction of binding pressure might lead to testing data of better quality and determination of COF, the results from the current friction tests using flat binder (with 5 MPa binding pressure) again implied that the tested steels had better friction performance than the tested aluminum grades.

![Figure 7](a). EDDS2  ![Figure 7](b). EDDS1

**Figure 7.** Result of pulling force versus displacement for two EDDS grades from strip drawing tests

![Figure 8](a). Al 5xxx  ![Figure 8](b). Al 6xxx

**Figure 8.** Result of pulling force versus displacement for aluminum grades from strip drawing tests

| Material     | EDDS-2 | EDDS-1 | BH340 | Aluminum 5000 | Aluminum 6000 |
|--------------|--------|--------|-------|----------------|----------------|
| COF          |        |        |       |                |                |
| 22 °C        | 0.11   | 0.12   | 0.135 | NA             | NA             |
| 54 °C        | 0.11   | 0.125  | 0.138 | NA             | NA             |

*Table 3. COF from strip drawing tests*

It is noted that all friction tests of both types were performed at the speed of 200 mm/s, while the machine actuator requires some time to accelerate to the relatively high speed. Therefore, it is essential to verify whether the steady speed of 200 mm/s was reached and maintained during the test. Figure 9 describes the history of displacement of specimens under testing. It shows that specimens reached the speed of 200 mm/s before 20 mm, and the speed was well maintained thereafter. Since the steady speed...
was aligned with the steady state of friction (Figures 4, 6 and 7) which started after 20 mm for both drawbead and strip drawing tests, the condition of valid speed for friction test was well satisfied.

Figure 9. History of displacement (pulling distance)

4. Conclusions
Friction tests were conducted on three mild steels and two aluminum grades using drawbead and flat binder (strip drawing) conditions at room temperature and an elevated temperature. The results from drawbead friction tests showed that, when there was no temperature compensation for clearance, for steels the friction force did not change after the temperature was elevated from 22 °C to 54 °C, while for the aluminum grades the friction force increased by 10% at 54 °C compared to at 22 °C. The results from strip drawing friction tests showed that, the COF could be readily determined for three steels with the testing data, while for aluminum grades the variability was too high to determine the COF. This indicated that the tested steels might have better control of formability in terms of friction performance.

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