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Effect of process variables on interface friction characteristics in strip drawing of AA5182 alloy in warm forming temperature range

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Abstract. Warm forming is widely used to enhance formability of aluminum alloy sheets in order to manufacture components with complex shapes. However, forming of aluminum alloy sheets by various sheet metal forming processes such as deep drawing and stretch forming involves sliding, drawing or stretching of sheet materials over the tool surfaces. Warm forming results in change of frictional characteristics at the tool-blank interface during forming. Higher friction leads to poor formability, non-uniform strain distribution, higher forming load, and poor surface finish of the component. So it is important to investigate the effect of process variables on friction at the interface in warm forming of aluminum alloy sheets. In this work, the tribological behavior of an Al-Mg-Mn alloy (AA5182) has been studied by performing strip drawing experiments in the warm forming temperature range (100-250 °C) in lubricated condition. Experiments were conducted to investigate the effect of temperature, normal force, and drawing speed on the coefficient of friction. A significant impact on the friction coefficient is observed by the change in boundary conditions as a result of variation in process variables with temperature being the most influential. The results have been compared with frictional characteristics in strip drawing at ambient temperature.

Introduction

Aluminum alloys have proven to be the ideal choice for weight reduction in the automotive and aerospace industries due to their higher strength-to-weight ratio than steels, good mechanical properties, and excellent corrosion resistance [1]. Complex sheet metal parts are required for automotive applications [2], and these are manufactured by processes such as deep drawing, stretch forming and bending [3]. Deep drawing is one of the most important sheet metal forming processes, and it involves radial drawing of a blank into the die cavity with a punch, as shown in Fig. 1 (a). Deep drawing is primarily used to create parts with a large depth, such as fuel tanks, oil sumps, gas cylinders, automotive panels etc. As the blank material in the flange region slides over the dies during deep drawing, friction between the blank and the tools affects drawability, uniformity of strain distribution, and drawing load [4]. However, the aluminum alloys have low formability at ambient temperature compared to the elevated temperature [5]. Jang et al. [6] studied the tensile deformation behavior of AA5182 aluminum alloy in the warm working temperature range of 150 – 350 °C. Warm forming of AA5182 aluminum alloy at temperatures below the recrystallization temperature combines advantages of both cold working and hot forming to a certain extent. D. Raja satish et al. [7] observed a similar behavior for AA5182 in the temperature range of 200 – 300 °C. The drawability of AA5182 has also been observed to increase in warm deep drawing. However, the frictional characteristics in deep drawing are very critical in warm forming because temperature, sliding speed, lubrication and binder force affect the interface friction in the flange region.

The friction and galling in forming processes are known to be affected by various parameters in the sliding contact region including contact pressure, sliding velocity, temperature, tool geometry, the sliding surface of the contact pair [8], and lubricant [9]. The adhesion of aluminum alloys to tool surfaces is enhanced during warm forming. This causes increased friction, degrades the surface quality of the formed part, and damages the tool [10]. As a result, lubrication and application of coatings has been a standard practice to reduce metal adhesion, tool wear, and friction [11]. Januszkiewicz et al. [12] studied the friction and wear behavior of AA5182 aluminum alloy ring rubbing against SAE (AISI) 52100 type bearing steel ball at various temperatures (up to 300 °C) and different applied forces (4 N and 24 N) in ball on ring frictional tester. The author noticed a transfer layer growing on the tool surface and severe scratches on AA5182 at a critical temperature of 230 °C. The findings demonstrated that temperature significantly impacts adhesion and wear.

Some test methods for assessing friction characteristics that have been developed over the years include pin-on-disk [13], ball-on-disk [14], block-on–disk [15], ball–on–plate [16], and strip drawing [17]. The parameters used in friction testing must be similar to the actual process parameters for reliable estimation of friction coefficient. The contact condition in strip drawing is similar to that encountered in the flange region during deep drawing. Assumption of a constant friction coefficient cannot accurately reflect the friction and galling behavior at the interface and predict the forming behavior in the warm forming process. Therefore, in the present work, strip drawing tests were carried out to investigate effect of important process variables on friction coefficient value under lubricated condition in the warm deep drawing temperature range of AA5182 aluminum alloy sheets. Tribological tests were carried out by varying temperature, normal pressure, and drawing speed. The friction coefficient is determined for different contact conditions and the results are compared with those at ambient temperature (25 °C).

Methodology

Material and specimens. Specimens of 1.2 mm thick AA5182 (Al–Mg–Mn) alloy sheets were used in the present work. This grade of aluminum is widely used in the automobile industry for sheet metal stamping due to its work hardening ability [2]. Samples of 500 mm x 65 mm were sheared from the metal strips for carrying out strip draw tests. The initial average surface roughness of the specimens was 0.95 ± 0.05 µm.

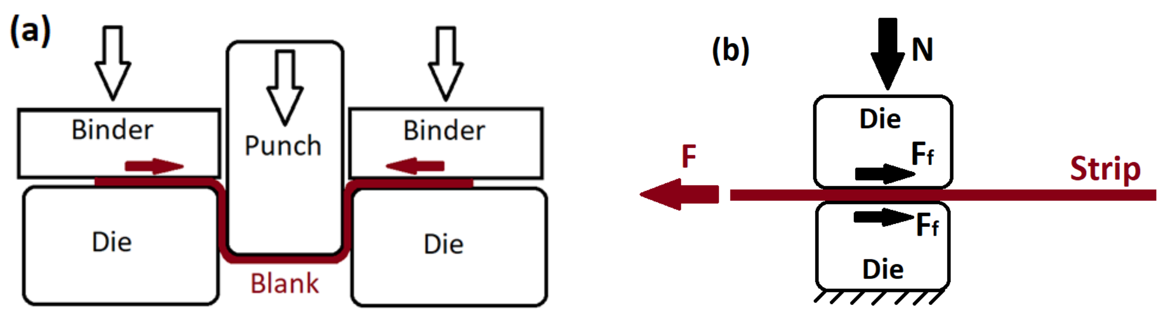

Fig. 1. Schematic of (a) deep drawing process (b) strip drawing test

Strip drawing tests. Fig. 1(b) depicts the schematic of the strip drawing test used in the present work. One end of the strip was clamped with wedge grips and a predefined normal force was applied on the strip placed between the dies. The strip was pulled using the wedge grips over a distance at a specified speed, and the draw force was measured. The friction coefficient was calculated using half of the draw force due to the frictional force acting on both sides of the strip. Flat dies of cross-section area 100 mm x 55 mm made up of high carbon, high chromium tool steel were used in the tests. The die surfaces had an average surface roughness (Ra) of 0.30 ± 0.05 µm after being ground and polished. The dies and the samples were cleaned with acetone before performing the experiments to remove any dirt that might affect the friction coefficient

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measurement. Oil-based lubricants KTL N16 and SHF 430 were used for testing at ambient and elevated temperatures respectively.

The amount of lubricant used was equivalent to 2.0 g/m2, which is the amount typically used in sheet metal stamping operations. The dies were preheated by cartridge heaters. Insulating isolation plates and cooling plates were installed to keep the surrounding electrical and mechanical components from overheating. When the desired temperature of the dies was reached, the strip was heated to a sufficiently high temperature taking into account the loss of temperature while placing it between the dies. The strip was pulled over a distance of 200 mm. From the force-displacement data obtained over the sliding distance range of 50 mm to 150 mm, the average friction coefficient was determined. The experiments were repeated three times for each combination to ensure the reproducibility of the results.

Process parameters. The strip drawing experiments were conducted to determine friction coefficient at different temperatures, speeds and forces. Although the recrystallization temperature of aluminum alloy is generally in the range of 300 °C to 400 °C, the material's strength decreases rapidly beyond 300 °C. Thus, to balance both strength and ductility, the recommended warm forming temperature of aluminum alloys is in the range of 100 °C to 250 °C. Thus, the strip draw tests in this work were carried out in this range. The blank holding pressure applied in the flange area during warm deep drawing of AA5182 aluminum alloys usually varies from 1.5 MPa to 2.5 MPa. Therefore, the normal force in strip drawing experiments is determined based on this pressure range and the die contact area (5500 mm2). Thus, the strips were drawn with a normal force in the range of 7.5 kN to 12.5 kN. The strips were drawn by varying the speed in the range of 2.5 mm/s to 10 mm/s to capture the effect of speed also on the tribological behavior.

Results and Discussion

Effect of temperature. The variation of friction coefficient with temperature in strip drawing experiments under lubricated condition is shown in Fig. 2(a) at two normal forces with a constant drawing speed of 10 mm/s. At ambient temperature, the friction coefficient is found to be 0.12 and 0.15 at 7.5 kN and 10 kN normal forces, respectively. The tests at elevated temperatures indicated the friction coefficient in the temperature 100-125 °C is lower than at ambient temperature. This could be due to material softening and lower shear stress required to draw the strip. At 10 kN normal force, with further increase in temperature, friction coefficient is found to increase before becoming nearly constant. The susceptibility of adhesion increases with increase in temperature leading to a gradual change in the interface condition and rise in friction coefficient. The friction coefficient sharply increased to 0.22 when the temperature is raised to 150 °C and it further increased to 0.23 at 250 °C. The variation of the friction coefficient at 7.5 kN exhibits a similar behavior, with a minor shift in the overall shape of the curve. The friction coefficient is minimum (0.078) at 125 °C at a normal force of 7.5 kN.

The variation of friction coefficient with the sliding distance for different temperatures is depicted in Fig. 2(b). These experiments were carried out at a normal force of 7.5 kN and a drawing speed of 10 mm/s. The friction coefficient is nearly constant along the sliding distance at ambient temperature but slightly increased at higher temperatures. An increase in temperature causes the lubricant's viscosity to decrease at the contact interface, which reduces the lubricant film thickness and its lifespan along the sliding distance. A sharp increase in friction coefficient has been observed towards end of the sliding at 250 °C possibly, due to inadequate lubricant at the interface at later stages of strip drawing leading to dry sliding condition and galling. Similar behavior has been observed by Januszkiewicz et al. [12] on AA5182 aluminum alloys at temperatures over the critical temperature, where there is a significant metal transfer to the tool and severe scratches on the workpiece has been observed.

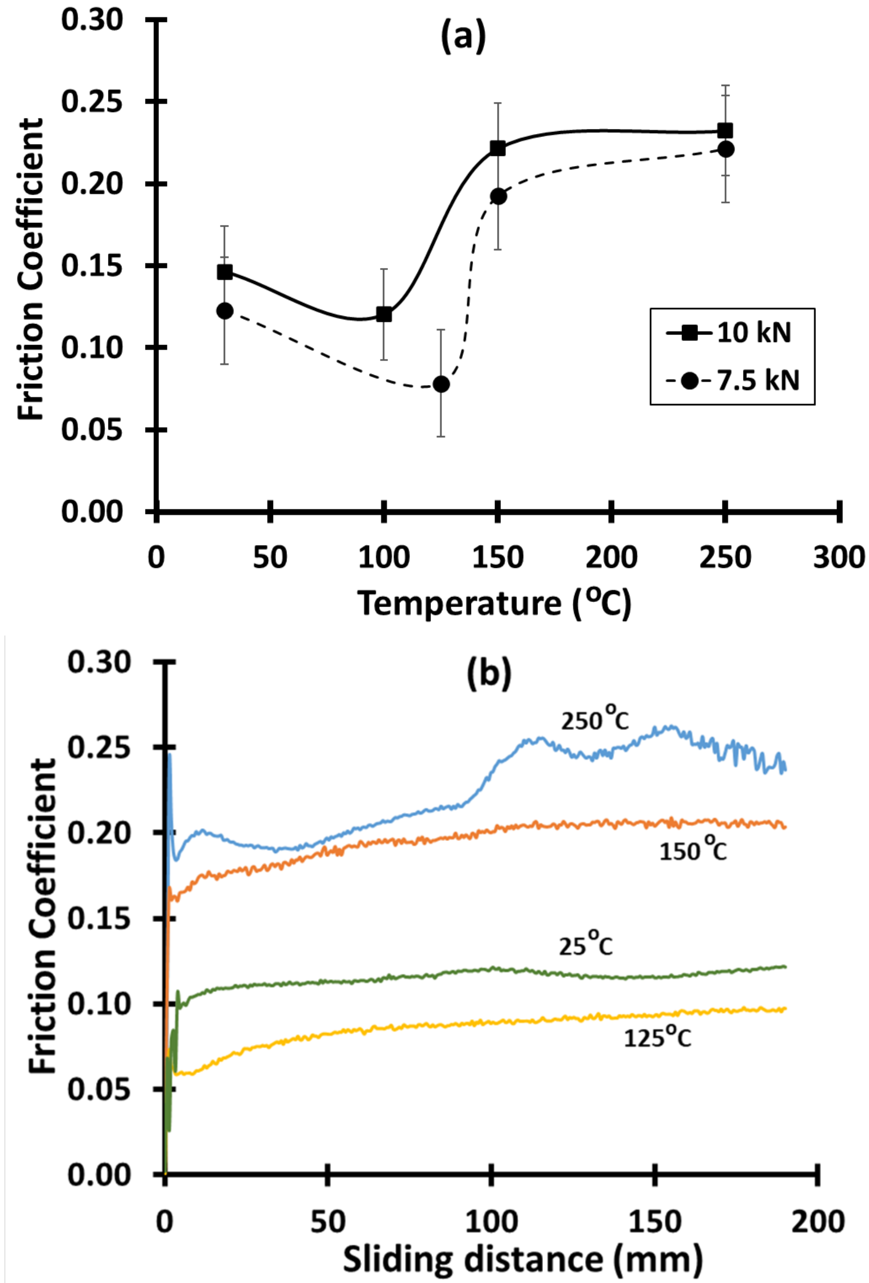

Fig. 2. (a) Variation of average friction coefficient with temperature at two different normal forces at 10mm/s and (b) Variation of friction coefficient with the sliding distance during strip drawing experiments at different temperatures

Effect of normal force. The variation of average friction coefficient value with normal force at elevated temperatures is shown in Fig. 3. Initially when the force is increased from 7.5 kN to 10 kN. The friction coefficient is raised by localized sticking due to high contact stresses produced under higher normal force. A similar trend is observed at the ambient temperature also. But at elevated temperatures, the friction coefficient is observed to decrease with further increase in the force to 12.5 kN. At high temperatures, the affinity of adhesion increases as the normal force increases. Asperities will undergo excessive plastic deformation, so higher shear forces are required due to stronger workpiece-tool interface bonding. But the decrease in friction coefficient could be attributed to subsurface shear deformation which requires a lower shear force [18].

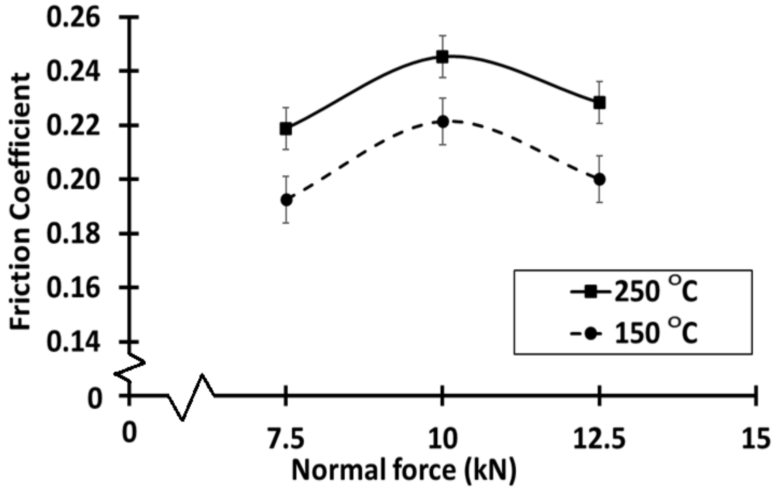

Fig. 3. Effect of normal force on friction coefficient in strip drawing in warm forming temperature range of Aluminum

Effect of speed. The effect of drawing speed on the friction coefficient at different temperatures is shown in Fig. 4. As drawing of the strip begins, the lubricant is drawn to the surface from the valleys, which act as a lubricant reservoir. As less amount of lubrication being distributed in the contact area at low speeds, higher friction coefficient has been observed due to stick/slip phenomenon of the contacting asperities. The flow rate of the lubricant from valleys to the surface increases with speed, thus reducing the friction coefficient. However, the decrease in friction coefficient with increasing speed at higher temperatures is lower than at ambient temperature. The lubrication mechanism's effectiveness at the contact interface plays an important role. Increasing tendency of oxidation and sticking friction that cause adhesion with increase in temperature might offset the decrease in friction coefficient with increase in drawing speed.

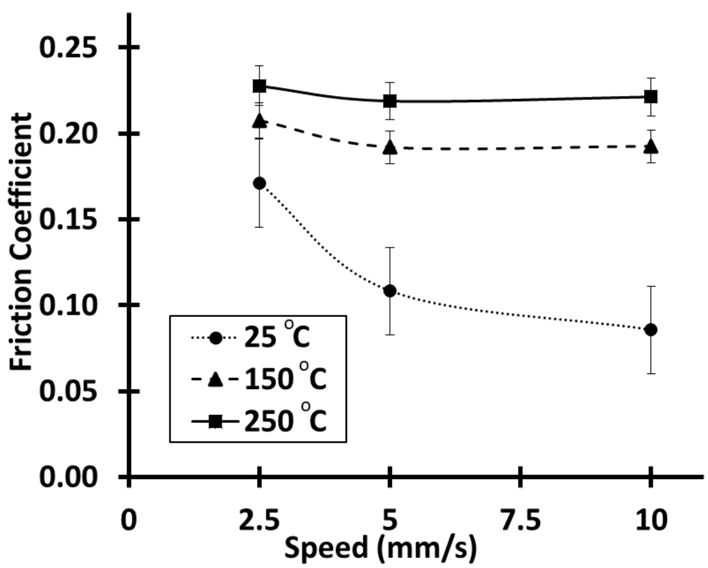

Fig. 4. Effect of drawing speed on friction coefficient in strip drawing at three different temperatures

The variation of drawing speed on friction coefficient with sliding distance at 150 °C and 250 °C, is shown in Fig. 5 (a) and (b) respectively. The peak static friction coefficient at 150 °C is 0.17 ± 0.01 while it is 0.2 ± 0.01 at 250 °C. This increase in static friction coefficient is due to higher adhesion with increase in temperature. The force required to draw the strip should overcome the static frictional force. The pulling force required to draw the strip decreases once the sliding begins. The kinetic frictional force is found to depend on the sliding speed. Fig. 5 shows that the kinetic friction coefficient dropped to 0.15 at 10 mm/s. As the sliding continues, increase in adhesion affinity leads to increase in kinetic frictional forces. This leads to a rise in the friction coefficient again with sliding distance, as shown in Fig. 5.

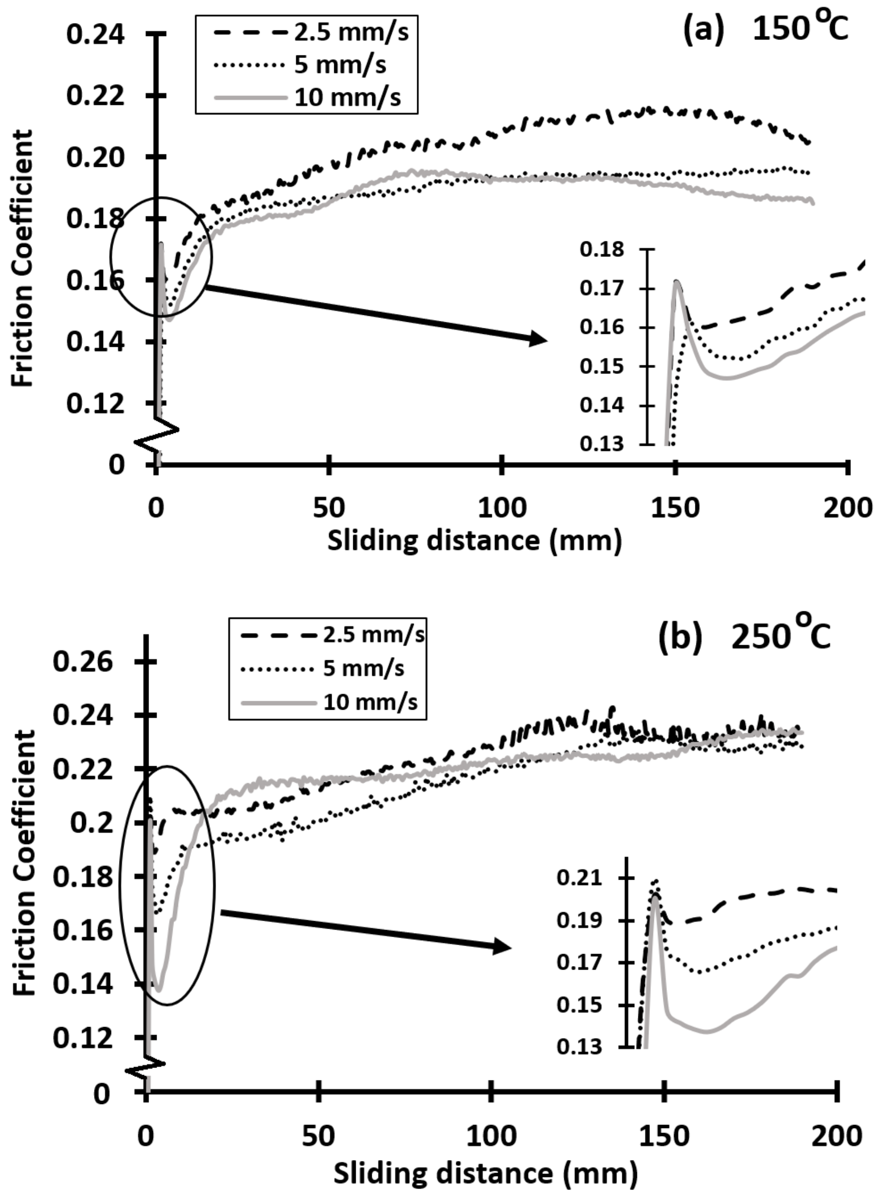

Fig. 5. Variation of friction coefficient with sliding distance for different speeds in strip drawing experiments at (a) 150 ºC and (b) 250 ºC

Conclusions

The effect of process variables on friction coefficient at the tool-strip interface in the warm forming temperature range of AA5182 aluminum alloy has been examined in the conditions similar to that exist in the flange region in warm deep drawing. The following are the main findings from the results and discussion presented in the previous section:

The friction coefficient is significantly influenced by the temperature. It decreased initially when compared to the ambient temperature. As the temperature rises further, adhesion becomes more susceptible increasing the friction coefficient. The peak static friction coefficient is also observed to increase with the increase in temperature. The friction coefficient is found to increase when the normal force is increased due to increased area of contact and localized sticking. But at elevated temperatures friction coefficient decreased with further increase in normal force due to subsurface shear deformation. The friction coefficient decreases as the drawing speed increases but the extent of decrease in warm forming temperature range is lower when compared to that at ambient temperature.

The outcome of this work can be used to improve the accuracy of predictions from numerical simulations of warm deep drawing of this alloy by incorporating the effect of process variables on friction instead of considering a constant friction coefficient value for a given blank temperature.

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