Effect of water-based lubrication on friction behaviour of 7075 aluminium alloy sheet in hot stamping

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Hot stamping technology is an effective way to achieve lightweight vehicles using aluminum alloy. Aluminum alloy is increasingly used in automobile manufacturing due to its high specific strength and recyclability. However, severe high-temperature friction and wear during the hot stamping forming process can scratch the surface of the formed parts, limiting its further promotion. Although solid lubricants, such as graphite, can improve friction, the 'double carbon' target proposed in recent years has raised the bar for the environmental friendliness of the production process. Furthermore, the experimental device and method are the core of tribology research in hot stamping. This article aims to study the friction behavior of 7075 aluminum alloy under water-based lubricant conditions using a self-designed vertical friction tester that overcomes gravity bending. we designed and developed an independent vertical friction experimental machine. By changing the loading method of the plate, the machine greatly improves its bending resistance and ensures accurate experimental results. By using the friction tester, the effect of process parameters on the lubrication behavior of water-based lubricants was investigated and compared it with commercial BN lubricants. The results showed that temperature and speed parameters had the most significant impact on the lubrication behavior. At 300℃ and 350℃, the coefficient of friction remains low throughout the sliding process due to the intact lubrication film. The dominant form of friction is abrasive friction. However, at 400℃, the lubrication film detachment increases, leading to the emergence of viscous friction. Furthermore, as the sliding speed increases, the shedding and transferring of the lubricant film decreases noticeably, resulting in a consistently smoother coefficient of friction at a speed of 100 mm/s. It is also worth noting that the coefficient of friction is lower at a sliding speed of 100 mm/s. Finally, the cumulative frictional wear behavior of 7075 aluminum alloy under lubrication conditions was investigated. The friction coefficient increased significantly with continued sliding distance, and the appearance of stickies was found to be the main cause of plate scratches. Two main modes of lubrication for water-based lubricants are the transfer of the lubricating film on the surface of the friction pair during sliding and the filling of the peaks and valleys of the stickies by the lubricating film.

Keywords: 7075 aluminum alloy; Hot stamping; Water-based lubricants; Friction behavior.

1. Introduction

Aluminum alloy is a commonly used material in automobile manufacturing due to its low density, high specific strength, and high corrosion resistance. Its advantages make it an important lightweight material. However, the formability of high-strength aluminum alloys at room temperature is poor. Hot forming technology can effectively solve the problems encountered in cold forming [1]. The basic principle of hot forming is to insulate and solidify the sheet in a heating furnace. Then, transfer it to a die for forming and pressure-holding quenching. Finally, perform aging treatment to obtain a high-strength part.

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To promote the development of aluminum alloy hot stamping technology, researchers have explored the forming process, precipitation phase transition, and strengthening mechanism. Geng et al [2-3] investigated the mechanical properties and formability of aluminum alloy sheets under hot stamping conditions using a contact heating solid solution equipment. Compared to traditional radiant heating technology, contact heating can achieve a uniform temperature distribution of the sheet and reduce the solid solution time of aluminum alloy. Self-resistance heating technique was proposed for the improvement of the solidification aspects of aluminum alloys by Maeno et al [4]. Liu et al [5] studied the fast solution heat treatment of high strength aluminum alloy sheets in radiant heating furnace during hot stamping. Choi et al. [6] conducted an experimental investigation into the anisotropic and non-proportional deformation behavior of 7075 aluminum alloy after tempering heat treatment. They obtained the corresponding intrinsic model and predicted the springback of the part through numerical simulation. Gronostajski [7] prepared an automotive B-pillar using 7075 aluminum alloy through hot stamping.

The serious softening of aluminum alloy at high temperatures, which results in poor friction behavior with the die, is one of the reasons that currently restricts the wide application of aluminum alloy hot stamping technology. During the hot stamping, the surface hardness of the aluminum alloy is lower than that of the die. As a result, surface particles break during forming, and the debris adheres to the die surface. This increases the resistance to sheet flow and can even scratch the sheet, which negatively impacts the surface quality of the part. Additionally, it can deteriorate the surface accuracy of the die, leading to increased frequency and cost of die repair. Ghiotti et al. [8, 9] designed an experimental setup to investigate the effect of hot stamping process parameters on the frictional wear behavior of 7075 aluminum alloy at high temperatures.

To decrease friction during the hot stamping process of aluminum alloys, two methods are commonly used: lubricants and coatings with lubricating effects on the dies. Oil-based lubricants lose their lubricating properties prematurely in high-temperature environments. Therefore, solid lubricants such as graphite, MoS2, and BN have been studied and utilized more [9]. Graphite has been found to have more stable lubrication properties. A better adhesion ability between graphite and the substrate can significantly delay lubrication failure. Gali et al. [10] used the gas spraying method to prepare GO and WS2 solid lubricant coatings on the surface of aluminum alloys. The results showed that both lubricated coatings exhibited lower coefficients of friction during sliding contact due to the formation of a transfer layer on the surface of the friction tool and a friction layer on the surface of the aluminum alloy. Furthermore, WS2 was observed to exhibit superior wear resistance, which was attributed to the coating's adhesion to the substrate. Schell et al. [11] assessed the efficacy of solid lubricants, including waxes and polymers, in a strip tension friction experiment. The experimental results indicate that the waxes demonstrated greater stability to the experimental temperature than the oil-based lubricants. Meanwhile, the polymer lubricants formed a thin barrier layer on the plate surface, effectively separating the sheet from the die surface and reducing the direct contact of the surface micro-convex bodies.

This resulted in a stable coefficient of friction over the entire experimental sliding distance, with only minor wear observed.

Although high-temperature lubricants can improve the friction of aluminum alloys during hot stamping, the use of solid lubricants, such as graphite, can result in the lubricant remaining on the surface of the part after molding. This can make subsequent removal more difficult and can negatively affect later painting processes. Additionally, graphite and chlorine-containing lubricants can pollute the environment, which hinders the development and realization of the 'dual carbon' goal. Therefore, this paper firstly develops a vertical friction experimental machine based on the demand of aluminum alloy hot stamping friction experiments, and verifies its reliability and practicality; and then researches the anti-adhesive lubrication mechanism of water-based lubricants under hot stamping conditions based on the vertical friction experimental machine. These works will provide new ideas and theoretical support for the study of aluminum alloy hot stamping friction.

2. Experimental materials and equipment

The friction pair material is H13 mold steel. To simplify replacement and conserve material, the friction pair is designed as a split structure, comprising a friction pair fixing body (Figure 1(a)) and a friction pair (Figure 1(b)). The friction pair base is bolted to the pressure loading module and will only be replaced if its shape and dimensional accuracy change after long-term use. The friction pair's working surface measures 15.8×15.8 mm and has 1 mm chamfered edges.

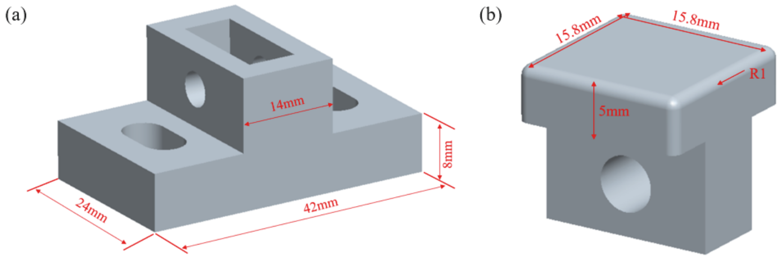

Figure 1 Schematic diagram of friction pair and base dimensions: (a) friction pair fixing body; (b) friction pair

The experiment employed 7075-T6 aluminum alloy sheets that were 1.5 mm thick and cut into 20 mm wide strips with a length of 600 mm perpendicular to the rolling direction of the sheet. To prevent cutting burrs from affecting the experiment, the width of the cut sheet was slightly larger than the width of the friction pair. Before each friction test, the strip's surface was wiped clean with alcohol.

The lubricant used is a water-based lubricant (No. 786) produced by the company. It is specifically formulated for use in the extrusion of aluminum or magnesium alloys. Due to the small size of the particles in its composition, agglomeration and sedimentation may occur after long period of standing. To prevent this, the lubricant is dispersed in a magnetic stirrer for 15 minutes before each experiment.

Plate stretching is considered one of the most effective experimental methods for simulating hot stamping conditions among many friction test methods. Many friction experimental devices have a common feature: pressure loading is along the vertical direction, which neglects the phenomenon of plate deflection caused by gravity and affects the accuracy of the friction experimental data. The group designed and developed a vertical friction experimental machine, as depicted in Figure 2. The machine's overall structure comprises a heating module, a friction pair and pressure loading module, a plate fixture, and a servo drive module.

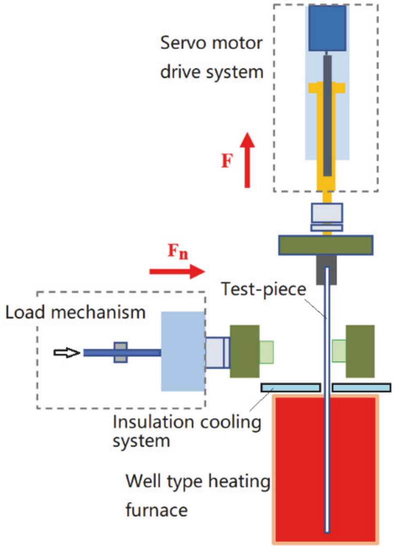

Figure 2 Overall structure of vertical friction testing machine

The friction tests' specific process parameters are shown in Table 1. The study investigated the anti-adhesive friction effect of a water-based lubricant by varying the temperature, sliding speed, and pressure of the sheet. Additionally, friction experiments were conducted under BN lubrication conditions at different temperatures to compare the friction reduction effect of the water-based lubricant with that of commercial BN lubricants.

Table 1 Friction test process parameters

sheet Temperature (℃)	Friction pair's temperature	sliding speed (mm/s)	positive pressure (N)	lubricants
300/350/400	RT	75	15	786/BN
400	RT	75/100	15	786
400	RT	75	6/10/15	786

3. Results and Analysis

3.1. *Effect of temperature on friction under lubricated conditions*

Figure 3 shows the relationship between the coefficient of friction and sliding distance of aluminum alloy plates at different temperatures, as well as the statistics of the average coefficient of friction values. The shedding of the lubricant film in the late stage of sliding leads to the phenomenon of viscous friction, which does not represent the true lubricity of the lubricant. Therefore, the statistics of the average value were selected from the more desirable area. As shown in Figure 3, the red dotted line represents the average coefficient of friction value statistics area. Figure 4 displays the surface morphology of the friction sub-surface, where the micro-morphology of each numbered position corresponds to the SEM image directly below it.

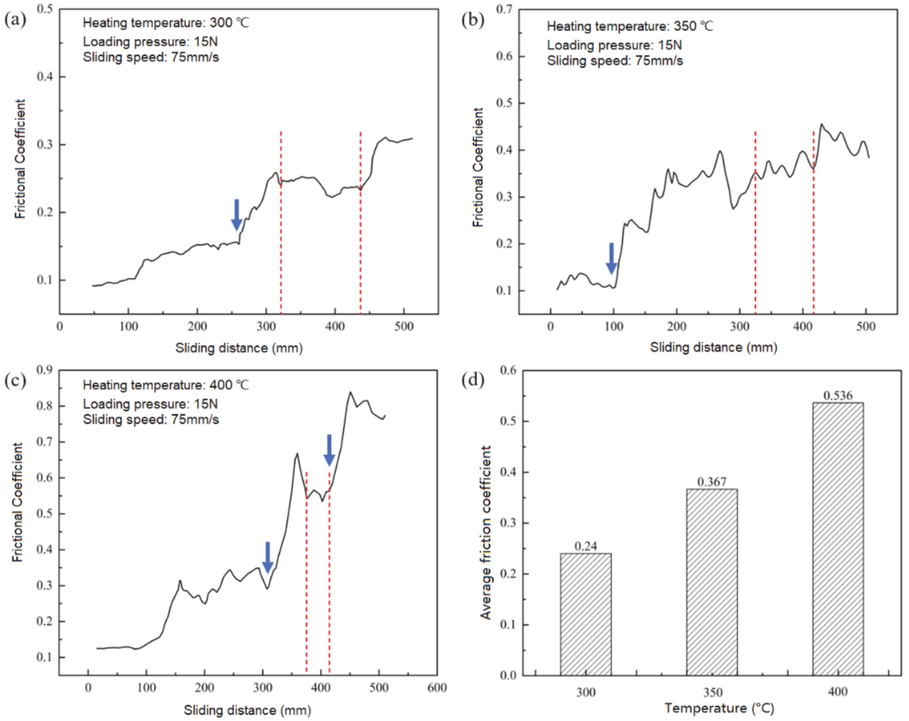

Fig. 3 Statistics of friction coefficient at different temperatures: (a) 300 ℃; (b) 350 ℃; (c) 400 ℃; (d) average friction coefficient

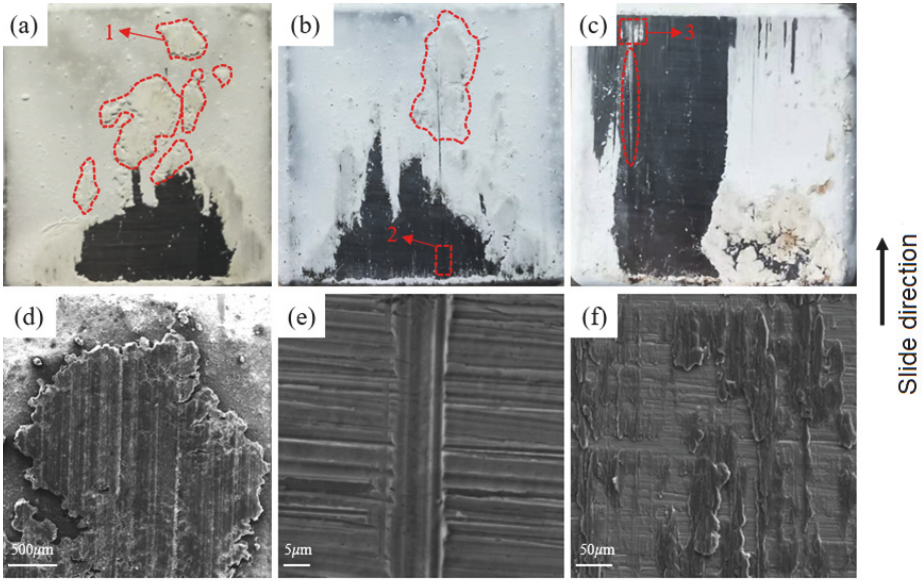

Fig. 4 Surface morphology of friction pair at different temperatures: (a) 300 °C; (b) 350 °C; (c) 400 °C.

Based on the analysis of friction at different temperatures, it is evident that the temperature variable significantly affects the friction of 7075 aluminum alloy under lubrication conditions. As temperature increases, the lubricant is more likely to shed and transfer, resulting in direct contact between the high temperature sheet surface and the friction pair surface with higher strength. This causes the average friction coefficient to gradually increase, and adhesive friction leads to a surge in the friction coefficient.

3.2. *Effect of speed on friction under lubricated conditions*

During low-speed sliding, some of the lubricant on the friction pair's surface is removed, resulting in a loss of lubrication during subsequent sliding. This causes the coefficient of friction to increase from 0.3 to 0.6, and eventually leads to the occurrence of more serious viscous friction. When the sliding speed increases from 75 mm/s to 100 mm/s, there is a significant difference. The coefficient of friction becomes more stable under the 100 mm/s sliding conditions, with a jittery rise from 0.14 to around 0.3, and then remains relatively stable. The residual lubrication film on the friction pair shows that only the lubrication film near the upper edge of the friction pair was removed, leaving a large area of complete lubrication film to ensure separation between the friction pair and the sheet surface.

3.3. *Effect of pressure on friction under lubrication conditions*

The general trend is that the coefficient of friction increases with increasing pressure. The friction marks' width on the sheet's surface tends to increase and then slightly decrease as the pressure increases. Meanwhile, the depths gradually decrease as the pressure increases. The friction coefficient's variation with sliding distance is affected differently by shedding and transferring of the lubricant film on the contact surface. This indicates the necessity of using lubricants in the hot stamping of aluminum alloys. Furthermore, the topography of the friction pair's surface reveals the presence of strip grooves between the grinding scratches. These grooves can potentially cause defects that lead to the occurrence of sticking phenomena. Additionally, they impede the length of the sticking material that can be applied along the sliding direction.

3.4. *Results and analysis of lubricant comparison experiments*

The study investigated the friction behavior of 7075 aluminum alloy and H13 die steel under BN lubrication conditions at varying temperatures. Figure 5 displays the friction coefficients during the statistical sliding process.

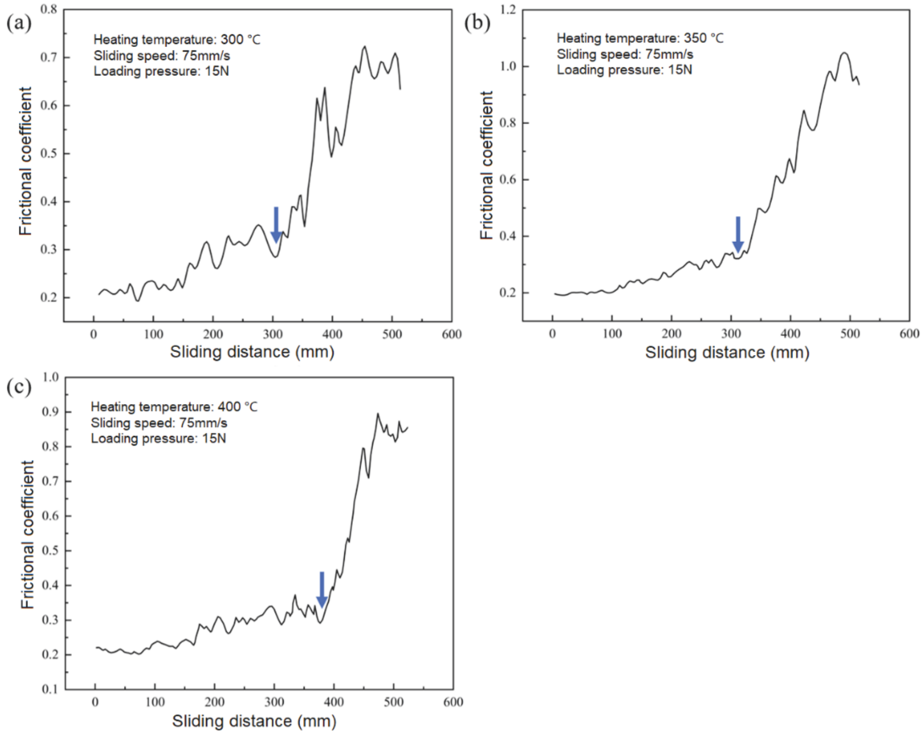

Figure 5 Statistics of coefficient of friction at different temperatures for BN lubrication: (a) 300 ℃; (b) 350 ℃; (c) 400 ℃

Based on the analysis above, it is evident that the residue of the effective lubricant film increases gradually with rising temperature under BN lubrication conditions. However, compared to water-based lubricants, BN is less effective in isolating the real contact between the sheet and the die surface. As a result, the degree of adhesive friction is higher under high temperature conditions than under water-based lubrication conditions, as evidenced by the width and depth of the scratches on the sheet's surface. Furthermore, upon comparing the super-deep morphology of the sheet, it is evident that the scratched area under BN lubrication conditions exhibits a significantly uneven tear, in stark contrast to the relatively flat scratch observed under water-based lubrication conditions.

4. Conclusion

The impact of sheet temperature and sliding speed on friction differs significantly. When the temperature is below 400 °C, the lubrication film on the surface of the friction pair is retained better, preventing real contact between the surfaces. This results in a friction coefficient between 0.3 and 0.4, and the surface of the sheet does not show any obvious scratches. However, at 400 °C, the lubricating film on the surface of the friction pair was significantly reduced, resulting in viscous friction. This not only increased the coefficient of friction to approximately 0.8 but also caused surface scratching on the sheet. The effect of pressure parameters on friction is similar, and viscous friction occurs at 400 °C. However, there are differences in the friction phenomenon under different pressures. As pressure increased, the width of the friction marks on the sheet's surface increased before slightly decreasing, while the depth gradually decreased.

Compared to 786 water-based lubricants, commercial BN lubricants exhibit higher coefficients of friction at different temperatures. This is particularly noticeable at 300°C when the lubricant film on the surface of the friction partner is completely removed, resulting in friction close to dry friction conditions. Furthermore, regarding sheet's friction marks, the width and depth of the sheet surface are higher under BN lubrication conditions. Upon comparing and analyzing the lubrication mechanism under both lubricant conditions, it was discovered that BN lubrication extends the length of the lubrication transfer film as the temperature increases, thereby reducing direct contact between the surfaces. However, the water-based lubricant provides continuous lubrication by maintaining a strong bond with the die, regardless of temperature.

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