Characterisation of new lubrication systems for hot forming of high strength aluminum alloys

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Abstract. Nowadays, fuel-efficient vehicles with high safety standards are required in the automotive industry. Lightweight materials like aluminum alloys play an important role for this development because of their high specific strength and low density. However, the application of high strength aluminum alloys is still restricted due to the limited formability at low temperatures. By the use of thermal supported forming processes, complex part geometries can be realized. Nevertheless, the high adhesion tendency of heated aluminum alloys and the lack of manufacturing-friendly and temperature-resistant lubrication systems limit the applications of hot-formed aluminum parts. New dry lubrication systems have been developed to overcome these challenges. In this contribution, the influence of different dry lubricants on the forming behavior of heated aluminum is analyzed. Therefore, the lubricants are investigated within a hot forming and quenching process. The results of the forming operations reveal that the necessary forming forces and the adhesive wear are reduced and therefore there is a high potential of the new dry lubrication systems for hot forming operations of aluminum alloys.

1. Introduction

In the automotive industry, there is a growing demand for the production of fuel-efficient vehicles with reduced energy consumption and CO₂ emissions. Aluminum with its characteristic properties of high strength to weight ratio, good corrosion resistance, and high recycling potential, is an appropriate material to replace conventional materials like steels [1]. The 6XXX aluminum alloy series have already been successfully used in the area of outer car body skin applications. For structural components, the use of 5XXX and 6XXX aluminum alloys also has been successfully implemented [2]. Nevertheless, crash-relevant parts have only limited been realized out of lightweight materials like aluminum. An innovative approach is the deployment of high-strength 7XXX aluminum alloys for crash-relevant components like B-pillars [3]. Conventional cold forming operations are not suitable for these aluminum alloys due to their low formability and the occurrence of spring back [4]. Therefore, novel forming methods are needed to manufacture complex formed parts. In 2009, Foster et al. patented a new process for forming aluminum alloys, which combines solution heat treatment (SHT), hot stamping and fast cooling [5]. The blank is heated up to a solution heat treatment temperature and then simultaneously formed and quenched in a cold die (HFQ®) (see Figure 1). Afterward, a strength increasing artificial aging step of the hot-formed component is possible. As a result, this forming method combines the advantages of thermally assisted forming by a substantial increase of the formability and at the same time, a reduction of spring back, with the strength-
increasing properties of heat-treated hardenable alloys [6]. Nevertheless, the industrial application of this forming method is currently still facing some challenges. On the one hand, heated aluminum alloys tend to high adhesive wear. On the other hand, there is actually only a limited number of lubricants available on the market, that ensures low tribological friction, easy washability and prevention of toxic gas generation during the hot forming operation [6], [7]. The lubricant manufacturer Holifa Fröhling GmbH & Co. KG has developed a new lubrication concept that fulfills these challenges and supports short-time hot forming operations. These lubricants are in a solid state of aggregate at room temperature. Due to the fact that these lubricants are currently still in the stage of development, it is not possible to provide more recipe information. Purpose of this research is the influence analyses of different dry lubricant compositions on the forming behavior of non-isothermal hot formed aluminum parts. Therefore, deep drawing tests are performed to analyze the maximal forming forces by using dry lubricants. To investigate the adhesive wear of the manufactured parts, gravimetric investigations are performed. Based on these results of the deep drawing tests and the gravimetric analysis, an evaluation of the functionality of the new lubrication systems for industrial application is derived.

![Figure 1](image1.png)

**Figure 1.** Schematic illustration of the non-isothermal hot forming process chain.

2. Materials, application technique and experimental setup

2.1 Material and lubricants

Within this investigation, the age hardenable high-strength aluminum alloy AA7075 in the delivered condition T6 with a sheet thickness of $t_0 = 2.0$ mm, is used. The three lubricants are free of graphite, boron nitride, molybdenum disulfide, PTFE and silicone. They are in a solid state of aggregation at room temperature and have various particle sizes. Lubricants A and B have an identical and fine particle size distribution between 15 µm - 70 µm whereas lubricant C has a coarser distribution between 300 µm - 500 µm. Lubricant A and B have different chemical compositions.

2.2 Lubricant application technique

Due to the short thermal resistance of the lubricants, they are applied before forming operation onto the cold tool. The dry lubricant only melts during forming when the heated aluminum sheet is simultaneously formed and quenched in the coated cold die. Afterwards, the lubricant cools down and changes back to a solid-state condition. In order to ensure a consistent contact of the particles on the tool surface, the lubricant is applied by an electrostatic coating mechanism, known as corona coating. That coating technology came out in the 1950s in the USA and is widely used in the industrial coatings, furniture and construction industries [8]. As shown in Figure 2, the uncharged particles are guided with the use of an airstream alongside a high-voltage electrode. Because of the ionization of the air by the high-voltage electrode, the particles of the lubricant are electrostatically charged.
escaping particles then stick on the surface of the grounded tool. The movement of coating particles is promoted by the combination of airflow force and electrical force from the coating gun towards the grounded tool owing to the presence of an electrical field between the charging gun and the grounded tool [8]. With this technique, an application of the lubricant without using any liquids is possible.

Figure 2. Schematic illustration of the electrostatic application system.

2.3 Definition of the deep drawing setup
For performing deep drawing tests, the hydraulic press type Lasco TSP100So with a cylindrical cup tool as shown in Figure 3, is used. By the use of distance ring not only concentric placement of the blank but also maintains a constant gap. This ensures that the blankholder force does not influence the punch force. The die is made out of the material 1.2367. Before every deep drawing experiment, the tool with an ambient temperature of \( T_{\text{die}} = RT \) is coated with a dry lubricant. For this purpose, an electrostatic coating gun, type Edelmann model 12-9000 with an operating voltage of 12 kV, is used for the investigation of the three different lubricant types. The drawing depth of the cups is determined to a maximum of \( x_{\text{max}} = 30 \) mm and the die velocity is constant \( v_{\text{die}} = 27 \) mm/s. During the forming operation, the forming force F is measured by the use of a 500 kN load cell.

Figure 3. Schematic illustration of the closed cylindrical cup tool with a distance ring
a) before forming
b) in formed condition.
The aluminum blank has a diameter of $d_0 = 90$ mm, an initial thickness of $t_0 = 2$ mm and is manufactured by laser cutting. Before the deep drawing tests, the specimens are heated up to solution temperature of $T_{SHT} = 470°C$ for $t_{heat} = 600$ s after a previous heating-up time of 300 s and an oven type Rohde ME17/13 SG. The heated blanks were transferred from the oven to the press with three varying transfer times of 5 s, 10 s, and 20 s. To analyze the effective specimen temperature at the mentioned cooling times, air cooling tests with thermocouples type K were performed. In order to consider statistical effects, the tests were repeated three times. The thermocouples are positioned inside the specimen to record the core temperature during heating and cooling process. As shown in Figure 3a), the inserted blank in the forming tool has only contact to the punch. Thus, a previous cooling of the blank in the forming zone during the closing step of the tool is prevented. Hence, the heated blanks are immediately formed and simultaneously quenched in the cold die. For statistical assurance, each test is performed at least 5 times.

2.4 Investigation of applied lubricant and material wear on the manufactured components
Gravimetric investigations were carried out to analyze the erosion of the manufactured components. Therefore, the parts are weighed before forming, after the forming operation and after cleaning (see Figure 4). The laboratory precision scale Kern AET 500-4 has been used for this purpose. For cleaning the cups after forming, an ultrasonic cleaner type Emmi 40hc in combination with a mild detergent water solution as cleaning medium has been used. The cups are cleaned in an ultrasonic bath without manual post-cleaning, at defined cleaning time and temperature.

![Figure 4](image_url)

**Figure 4.** a) Cleaned blank before hot stamping, b) formed cup with lubricant, c) cleaned cup.

3. Results and discussion
3.1 Results of transfer cooling tests
The results of the cooling tests of the specimens are shown in Figure 5. The illustration shows the blank temperature as a function of the respective transfer time. The cooling tests were performed three times ($n = 3$) for statistical assurance. The average component temperature during solution heat treatment is $T_{0s} = 469±2°C$. The cooling tests show that cooling at room temperature after 5 s leads to a temperature of $T_{5s} = 460±2°C$. This indicates that a cooling rate of approximately 1.8°C/s is expected for cooling in atmospheric air. Mohamed [9] identified a cooling rate of 10°C/s for aluminum in ambient air. This deviation can be caused by different test conditions, other temperature measurement methods, an alternative blank size or the use of the MgSi alloy AA6082. After a transfer time of 10 s, the part temperature reaches $T_{10s} = 440±3°C$. The cooling rate increases to a value of 2.9°C/s. The delayed increase of the cooling rate is due to the position of the thermocouples. Because the thermocouples are located in the center of the plate, the measured temperature is the core temperature of the sample. After a cooling time of 20 s, the specimen cools down to $T_{20s} = 412±2°C$. 
3.2 Results of the deep drawing tests

All forming tests performed with the aluminum alloy AA7075 were carried out without failure. Figure 6 illustrates the average required maximum forming forces for the deep drawing procedures as a function of the various dry lubricants and the different initial testing temperatures after various transfer times. The given test temperatures are the temperatures of the specimens after transferring them to the tool (see Figure 5). The forming tests with lubricant A and a transfer time of 5 s show, that an average maximum forming force of 35.5±0.6 kN is necessary. With an increase in the transfer time, a lower initial blank temperature, the average maximum forming force rises up to 35.7±0.9 kN. At a transfer time of 20 s, the average maximum forming force further increases up to 36.1±0.5 kN. However, the results of these investigations show that the described measurements are in the range of the standard deviation. Therefore, no significant conclusions about the forming behavior in dependence of transfer times are possible. Nevertheless, a trend towards an increase of the necessary forming force with decreasing component temperature is conceivable. The tendency towards an increase in the necessary forming force at lower component temperatures is relatable to the inferior formability of aluminum alloys at lower temperatures. Investigations by Sáenz et al. show for the high strength aluminum alloy AA7075 a drastic reduction of the true stress and higher formability at forming temperatures above 300°C [10]. Out of that reason, it is expectable that a decrease of the plate temperature caused by an increase of the transfer time would worse the forming behavior of the material. The lubricant B shows an average forming force of 34.5±1.1 kN at a transfer time of 5 s. After a transfer time of 10 s the average forming force is 35.1±0.7 kN and after a duration of 20 s up to 37.2±0.8 kN. In comparison to lubricant A, lubricant B shows a higher temperature dependency and a reduced forming behavior at decreasing temperatures. Furthermore, lubricant B has lower forming forces at initial forming temperatures between 460°C and 440°C and therefore better forming properties with less wear can be expected. The application of lubricant C results in significant higher forming forces in comparison to lubricant A and B. At a transfer time of 5 s, the average forming force is 48.8±3.2 kN. This leads to a force increase of more than 40% compared to lubricant B, under equal test conditions. With decreasing part temperature the necessary forming force increases up to 50±4.1 kN at initial part temperatures of 440°C. After a transfer time of 20 s, the average maximum forming force reaches 51.7±1.9 kN. The standard deviation using lubricant C is higher than for the other two lubricants. An explanation for this can be the application technique. With the electrostatic coating method, the application of bigger-grained patriarchels is limited. Furthermore, the transfer of the blank was carried out manually and for this reason, variation can be assumed. Moreover, also the coating of the die is realized by a manual process. Because of that reason the coating quality and consequently the forming properties might vary.
3.3 Running-in behavior of the different lubricants

Due to the fact that the die is completely cleaned before the application of a new lubricant type, it is possible to examine the running-in behavior with improving tribological properties of the different lubricants. In Figure 7 the running-in behavior of the three different lubricants regarding the maximum forming force is shown. For lubricant A, a running-in behavior is recognizable with a peak difference of the forming force of 7.2 kN. If the running-in behavior of lubricant A is represented by a linear regression curve, it is characterized by a negative gradient of $m_A = -1.187$. For lubricant B, the gradient of the linear regression curve $m_B = -0.068$ is less than for the Lubricant A. In addition, the difference of the forming force of 4 kN is also lower than for the Lubricant A. In addition, the difference of the forming force of 4 kN is also lower than for the Lubricant A. The most significant running-in behavior has lubricant C with a run-in gradient of $m_C = -3.146$ and a maximum force difference of 17 kN. The results show that the linear regression curves represent the running-in behavior of the deep drawing tests using different lubricants. One reason for the strong running-in behavior of lubricant C can be explained by the application technique. As mentioned before, coating with lubricant C is more difficult compared to the other lubricants. After the first coating and forming operations, lubricant sticks to the surface of the tool. In the subsequent forming operations, the lubricant still adhering and the newly applied lubricant produce better forming properties than before.

In summary, lubricant B has the best running-in behavior. In future, the running-in behavior of the lubricants should be confirmed by further industry-related tests to confirm the process reliability for manufacturing use.

**Figure 6.** Maximal deep drawing forces for the three different tested lubricants.

**Figure 7.** Running-in behavior of the three different lubricants for a transfer time of 5 seconds.
3.4 Results of the lubricant use and the wear analyses on the manufactured components

By using gravimetric analysis, the weight difference of the cleaned blank (Figure 4a)) and the formed cup (Figure 4b)) can be used to estimate the amount of lubricant during the forming operation. Figure 8 shows the weight difference between the cleaned blanks and the coated formed cups, depending on the used lubricants. The lubricant C, with an average remaining lubricant mass of 0.2625 g on every cup, represents the largest amount of lubricant. In contrast to that, by using lubricant B and A, an average lubricant mass of 0.1485 g and 0.1165 g was measured, respectively. One reason for the high amount of remaining lubricant of the lubricant C is the bigger particle size. With increasing particle size, the adhesion of the lubrication particles on the tool surface decreases because the weight force of the particles exceeds the necessary Coulomb force. To ensure a comparable lubricant coating thickness on the die by using lubricant C, more lubricant is needed in the coating process and therefore, more amount of lubricant is prone to remain on the formed cup. Furthermore, as mentioned in section 3.2, the coatings are applied manually which might be the reason for the high standard deviations of the results.

![Figure 8. Weight difference between initially cleaned blanks and formed, with lubricant coated cups after forming operation.](image)

After cleaning the formed cups by using an ultrasonic bath, the parts are weighed again. The difference in weight between the cleaned blanks and the cleaned, deformed cups (Figure 4c)) is demonstrated in Figure 9 for the three different lubricants. With the use of this analysis, the amount of wear, as well as remaining lubricant on the surface of the parts can be represented. For the lubricants A and B positive average weight differences of $g_{\text{diff,}A} = 0.86$ mg and $g_{\text{diff,}B} = 0.44$ mg can be detected. In contrast, a negative average weight difference of $g_{\text{diff,}C} = -37.12$ mg between blank and formed and cleaned cup is measured for dry lubricant C. The positive weight difference indicates a small remaining amount of lubricant on the parts. The negative weight difference indicates adhesive wear during forming operation. As a result, aluminum fragments stick onto the surface of the tool and influence negative the tool life. Also, the standard deviation for the produced parts with the lubricant C is disproportionally high, in comparison to the other lubricants.

![Figure 9. Weight difference between the cleaned blank and the cleaned formed cup.](image)
4. Conclusion

In the present research, experiments have been performed to study the forming behavior of the high strength aluminum alloy AA7075 by using newly developed dry lubricants for hot forming and quenching (HFQ®) operations. Firstly, deep drawing tests have been performed to investigate the maximum forming forces. It has been elaborated, that lubricant B with small particle size shows lower necessary forming forces than lubricant A and C for blank temperatures beyond 440°C. Furthermore, the results of the deep drawing tests exhibit the running-in behavior of the three different lubricants. It is noticeable that the small-sized particles of dry lubricant A and B reveal lower differences in the forming force than lubricant C with bigger particles. Additionally, lubricant B exhibits a lower running-in behavior than lubricant A. In addition, the gravimetric tests illustrated the abrasive wear on the blank during the forming operation and the increased amount of lubricant of the manufactured components with the lubricant C. In contrast, lubricant B showed the lowest wear behavior between the three lubricants. That leads to the conclusion, that lubricant B has a more positive influence for hot forming operations, compared to the other two lubricants. For further investigations, different particle sizes of the lubricant B should be investigated. In future, it is helpful to examine the resulting coefficients of friction using dry lubricants.

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