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Tribological Issues During Quick Plastic Forming

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Quick plastic forming (QPF) was developed as a high-volume, hot blow forming process for automobile components, enabling larger volume applications than traditional superplastic forming (SPF). One critical aspect of the process is the tribological interaction between the forming tool and the aluminum blank, as this impacts formability, surface quality, and tool durability. While QPF has been successfully implemented for automobile components, many opportunities exist for improving the tribological condition during the process, including the die coating or treatment, the lubricant, and the fundamental understanding of aluminum/iron adhesion under QPF conditions (450 °C). This work reviews key tribological issues affecting QPF and identifies areas where additional research is required.

Keywords aluminum forming, aluminum hot forming, blow forming, friction, hot forming, lubricants, lubrication, quick plastic forming, superplastic forming, surface quality, tool wear, tribology

1. Introduction

Quick plastic forming (QPF) (Ref 1) and superplastic forming (SPF) (Ref 2-7) are high-temperature forming processes that have been used to make a variety of aluminum automotive components at both high (QPF) and low (SPF) production volumes. Both processes rely on hot gas to form a heated blank into a single-sided forming cavity. The processes operate at temperatures in excess of 400 °C, and, as a result, special tooling and lubricants are required under these conditions. In addition, the nature of the processes is such that the aluminum is relatively soft during forming and intimately conforms to the tool surface. As a result, any foreign material present between the blank and the die results in a surface imperfection that has to be repaired prior to painting. This can arise from (a) debris on the forming tool, such as lubricant accumulation, metallic particles, and insulation debris; (b) material on the blank prior to forming such as inhomogeneous lubrication, metal fines, and slivers; or (c) irregularities on the tool surface such as galling, wear, and coating chips. Parts are typically designed so that the appearance side of the panel is not in contact with the die surface to minimize imperfections and so that any imperfections that do occur are protruding, leading to easier repair. This work reviews key tribological issues affecting QPF by describing the current state-of-art and then identifying areas where additional research is required. Four main areas are addressed: friction testing, lubrication, die surface engineering, and modeling.

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2. Friction Testing

2.1 Background

The majority of the tests used to measure friction for conventional sheet metal forming produce plastic deformation of the workpiece and motion of one of the components of the tribosystem. No single experimental procedure is widely accepted or applicable (Ref 8-11). This is even more apparent for elevated-temperature forming processes, such as QPF, where industry experience is limited. In addition, many of the standard tests do not capture the deformation state during QPF, where the material is stretching and sliding at the same time, leading to a dynamic tribological condition that is difficult to accurately represent.

2.2 State-of-the-Art

Many tests have been developed to evaluate the properties of tribosystems in metal forming, but only some of them have been applied to elevated-temperature deformation. In the following sections, each type of test is reviewed, first as it is applied to conventional metalforming using Schey's (Ref 9) classification of partial plastic deformation tests and then as it is applied to elevated-temperature forming where applicable.

2.2.1 Plane Strain Drawing Tests: Strip Drawing and Stick-Slip. In the strip drawing test, a sheet metal sample is pulled over the cylindrical surfaces of pins that simulate selected tool geometries: flat/flat, flat/cylinder, and cylinder/cylinder. The tests are usually performed to evaluate the lubricated contact between tool and metal sheet at a deformation rate representative of the forming process (Ref 12-15).

This type of test has been used to study the effect of temperature, strain rate, and normal pressure on the coefficients of friction for aluminum alloys at temperatures and strain rates representative of superplastic conditions (Ref 16). It was observed that the alloy composition, metallurgical structure, and surface finish of the die affected the coefficient of Coulomb friction. It would be difficult to extrapolate the results to QPF die performance since no stretching of the material was allowed during the test.

2.2.2 Draw Bending Tests: Draw Bead Simulator, Draw Bending, Friction Around Punch and Pins. Multiple friction simulators based on the stretching of a strip around a pin (Ref 17-21), bending under tension (Ref 9, 13, 22-25), and stretching under bending (Ref 25-26) have been developed to characterize sheet metal forming friction at room temperature. The draw bead simulator test, developed by Nine, is used extensively (Ref 11, 13, 27-30). A cylindrical cup and hemispherical dome sheet metal drawing apparatus has been used recently for evaluating boric acid dry films for room temperature forming of aluminum alloys (Ref 31).

Davies et al. (Ref 32) have developed a bending under tension experimental apparatus to evaluate the coefficient of friction between aluminum and tool materials during SPF. The effects of forming speed, temperature, pressure, lubricant, and tool surface finish on the coefficient of friction for the AA5083 and stainless steel at SPF temperatures were studied. Morales (Ref 33) used a small-scale pan die and inserts to evaluate relative performance of die materials, die coatings, and lubricants for QPF. The test approximates actual forming conditions, including material stretching over the representative tool material, but cannot be used to quantify the coefficient of friction.

2.2.3 Pin-on-Disk. A commercially available ball-on-disk friction tester based on a block-on-ring geometry was used to measure the room-temperature tribological properties of several coated steel blocks sliding against a rotating aluminum sample (Ref 34). General Motors developed a ring-on-disk tribotester to compare the friction coefficient of different die-material/lubricant/sheet-metal combinations and to obtain preliminary indication of their wear behavior under SPF and QPF temperatures and loads. The experimental apparatus allows acquisition of coefficient of friction data over the test duration and later evaluation of the wear scars by the scanning electron microscope and other techniques. A limitation of this setup is that the aluminum blank is not stretched during the test and sliding occurs repeatedly over the same location, neither of which are representative of the SPF or QPF process.

2.2.4 Twist Compression. Anand and Tong (Ref 35) recently developed a compression and torsion friction test to measure the die/workpiece interface frictional response under conditions resembling cold forming operations. Similar tests were used on heated specimens of aluminum, but, as in other tests, they fail to represent the actual forming process because no stretching of the aluminum occurs.

2.3 Research Opportunities

A test that represents the conditions of the forming process is needed for accurately measuring friction during QPF. The critical parameters include the ability to test at temperatures between 400 and 500 °C, and strain rates between 0.001 and 0.1 s^{-1}. In addition, and equally important, is the ability to continually stretch the aluminum sheet while sliding against the die surface. This will produce a dynamic interface in which oxides are constantly being broken and reformed. Another factor is the ability to measure the evolution of friction with subsequent deformation across a die, especially after galling or disruption of the die surface. Ideally, such a test could produce a friction coefficient that could be used in finite element simulations of QPF.

3. Lubrication

3.1 Background

Lubrication, whether applied to the blank or the forming tool, plays a critical role in the SPF or QPF process. The primary role of the lubricant is to reduce the coefficient of friction and allow material to slide across the tool surface, thereby avoiding failure. An example of this effect is shown in Fig. 1, where an identical pan shape was made using two different friction conditions: (1) a very light layer (~5 μm) of boron nitride (BN) lubricant was applied to the blank prior to forming, and no lubricant was used on the die, and (2) the die was coated with a thick layer of BN (~50 μm) and no coating was used on the blank. The panel formed under condition 1, shown in Fig. 1(a), could not be successfully formed without splitting. The surface of the panel after forming showed large scratches or galling marks where the blank moved past the forming tool. The panel formed under condition 2, shown in Fig. 1(b), could be successfully formed under identical conditions and the panel surface was very clean, with no evidence of galling or tool interaction. This prevention of galling is another characteristic of the QPF lubricant that is very important, as it should reduce die wear.

The reduction of friction by the use of lubrication during QPF plays a significant role in part extraction after forming. Proper part release is of critical importance at high production volumes. A lubricant that enables good part release allows simpler, lower-cost extraction mechanisms to be used.

Lubrication also plays a significant role in forming cycle time. The friction coefficient can affect necking when forming occurs over sharp radii. This phenomenon has been studied both experimentally and numerically (Ref 36-39) with the conclusion that increasing friction decreases the propensity for necking over sharp radii. This phenomenon is demonstrated in Fig. 2, which shows a panel formed into a symmetrical license plate pocket die that was treated to have a very high friction coefficient on half of the tool and a very low friction coefficient on the other half. The side of the panel formed on the high friction side, while exhibiting severe galling and sticking, did not exhibit necking while the side of the panel formed on the low friction side of the die exhibited necking. The low-friction side of the panel exhibited more uniform thinning in the bottom of the panel where the material was better able to flow into the die. It is therefore advantageous to have low friction for most of the tool, but high friction in specific areas.

Another characteristic of the lubricant, which has not been addressed significantly in the literature, is the effect on panel surface quality (Ref 7, 40). As mentioned earlier, any imperfection between the blank and die leads to an imperfection on the part after forming. The lubricant must be applied uniformly and not transfer to the tool during forming, otherwise surface imperfections will result. An example of accumulated lubricant is shown in Fig. 3.

The QPF lubricant also can aid in preheating of the sheet prior to forming. Rapidly heating a blank to temperature is critical to achieving high production volumes (Ref 1), and it

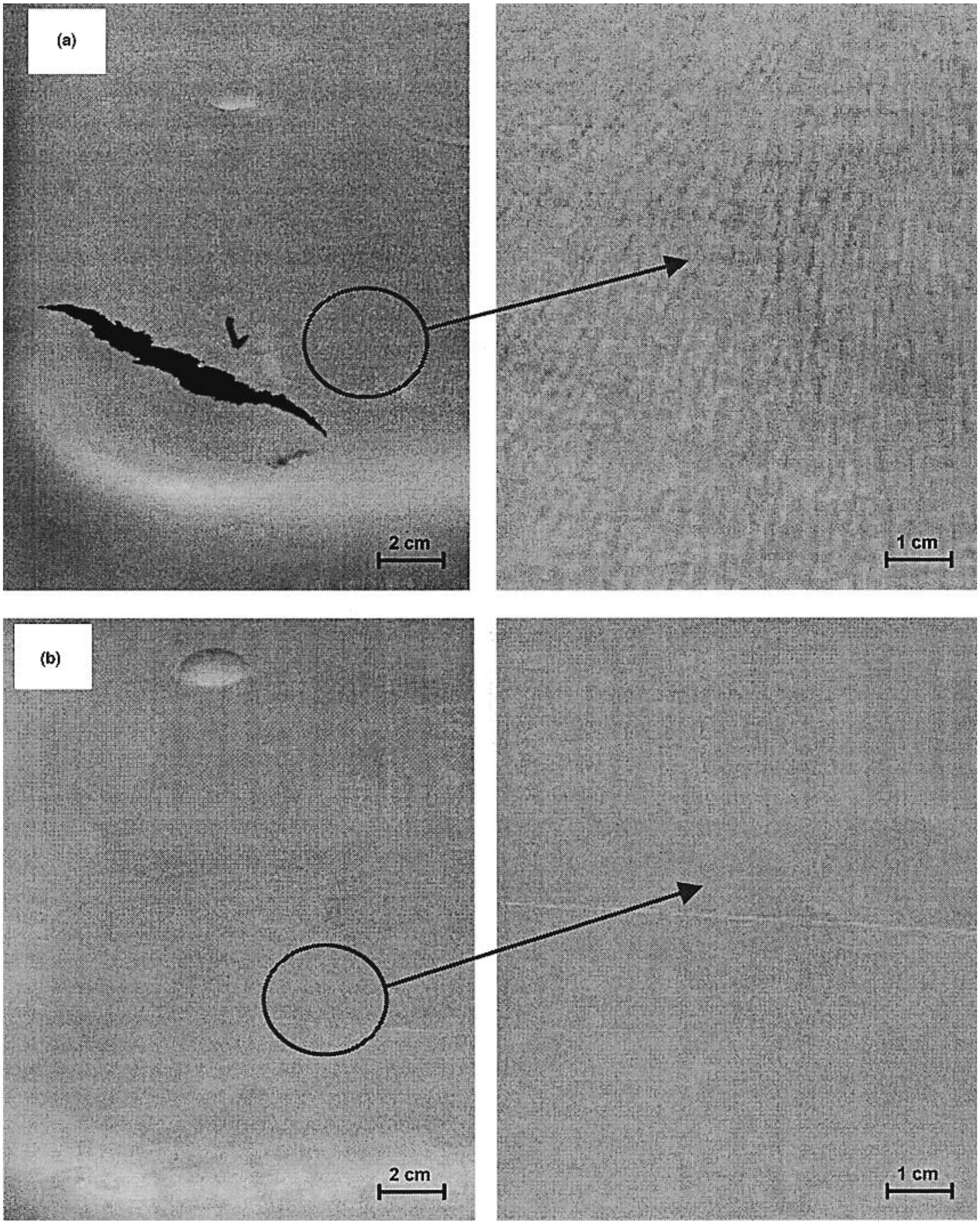

Fig. 1 Effect of lubricant on both galling and the ability to successfully form a QPF component. (a) Pan formed with light lubricant on blank. (b) Pan formed into die coated with thick layer of BN. The panel shown in (b) was successfully formed without splitting and did not show galling due to blank/die interaction.

depends, in part, on the emissivity of the aluminum sheet. The forming lubricant can increase the emissivity, thus enabling more rapid preheating (Ref 41).

A final characteristic of the QPF lubricant is its ability to be removed after forming, often referred to as "cleanability." The solid lubricants typically used for QPF such as BN or graphite must be removed after forming because they can hinder welding by increasing contact resistance or contaminating the paint system. This cleaning requirement is one reason why lubricants such as molybdenum disulfide are not used, as they are very difficult to remove after forming. Currently, all QPF panels require an acid wash after forming to remove the lubricant.

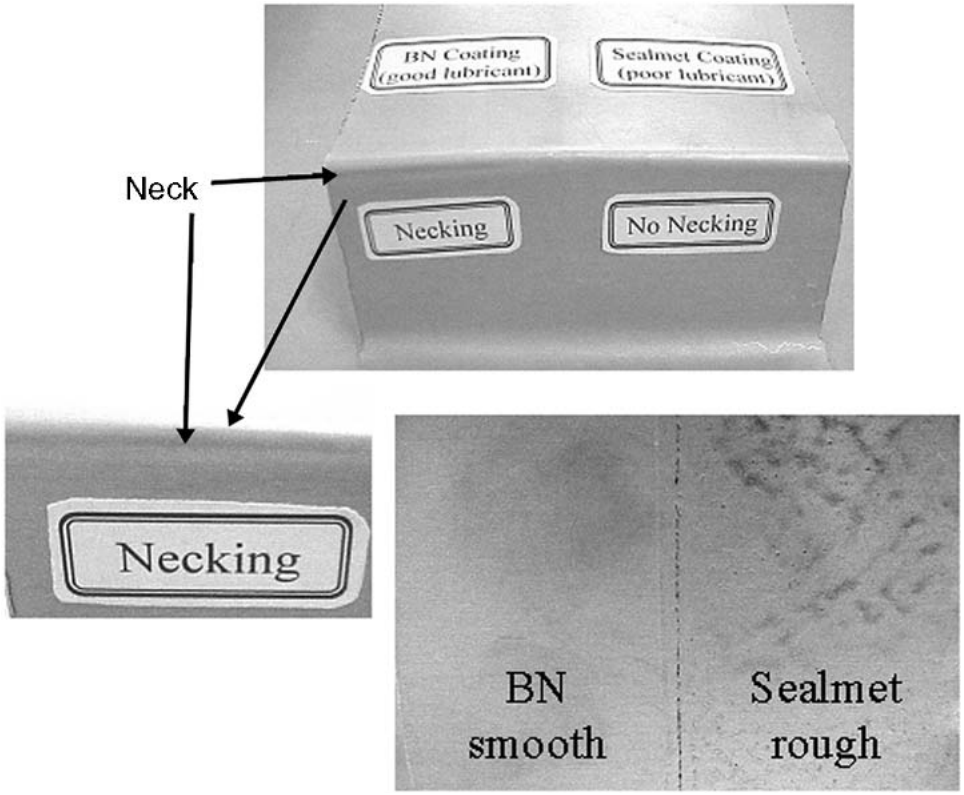

Fig. 2 Effect of friction on necking during QPF. Panels were formed on a die with two different levels of friction. On the high-friction side (Sealmet coated), no necking was observed. On the low-friction side (BN lubricated) necking was observed below the entry radius.

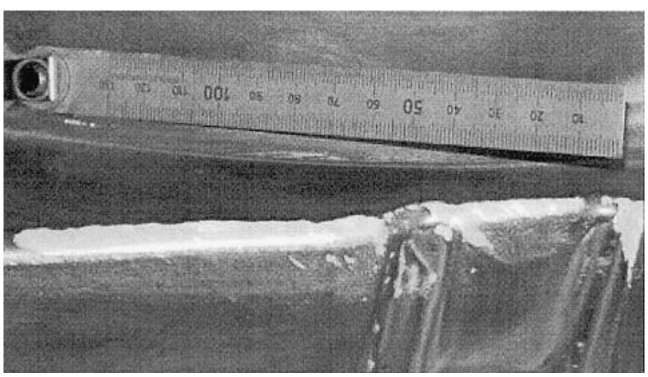

Fig. 3 Boron nitride lubricant buildup on QPF tool

3.2 State-of-the-Art

The SPF and QPF industries use BN and graphite for the vast majority of aluminum parts. Boron nitride provides excellent lubricity, adherence to the blank, uniformity of application, and ease of removal. The biggest drawback to BN is price. Graphite provides excellent lubricity and low cost; however, it is much more difficult to remove from the formed part than BN. In addition, it tends to flake after forming, leading to many particles of graphite in the air and on the tool.

In addition to the single-component lubricants, some lubricant mixtures have shown promising results. General Motors used a mixture of BN and milk of magnesia [$Mg(OH)_2$] (Ref 42) during production of the Oldsmobile Aurora decklid. Osada and Shirakawa (Ref 7, 40) reported that a mixture of BN and graphite was used to achieve good lubricity with excellent surface quality.

Spraying is the easiest method to apply the graphite or BN at high volume. The lubricant, BN, graphite, $Mg(OH)_2$, or mixtures of the three can be sprayed using standard paint application techniques and applied in either a manual or automated process. The process must be optimized to avoid an irregular spray pattern and to maximize material utilization, but can provide a very thin coating. For very low production volumes, the lubricant can be manually roller or brush applied. It is difficult to achieve a thin, uniform layer with such a technique, as it tends to leave either brush lines or roller imperfections. Very little has been published in the SPF literature about lubricant removal after forming. The current GM process uses an acid wash station, specifically developed for QPF panels.

3.3 Research Opportunities

While the currently available lubricants enable successful forming of QPF panels, they remain relatively expensive, especially when application technique is factored in. One technique that needs exploration is roll coating, which is used by metal manufacturers to apply pretreatments and lubricants to conventional sheet metal, or to prepaint sheet metal prior to stamping. A continuous application process could significantly reduce the cost of individually coating blanks, even in an automated process. A lubricant that may facilitate such a process would be a phosphate or similar conversion coating that could be coil applied. Such a coating could be applied uniformly. Ideally, such a coating would be compatible with subsequent painting and welding operations, eliminating the need for post-formed cleaning. It also would eliminate lubricant transfer to the die, reducing panel rework. The titanium industry has evaluated glassy-phase lubricants that melt during forming to provide a lubricious layer (Ref 43). To this point, no such lubricant has been identified for aluminum. Synthetic forging lubricants have been evaluated for QPF, but they tend to leave residue after heating that would lead to buildup on the tool and surface imperfections. Jovane and Ludovico (Ref 44) used superplastic lead-tin sheets as a lubricant for forming aluminum. While interesting, this would be impractical for high-volume application, but the idea may lead to a method for creating a boundary layer on the die that achieves the same effect.

4. Die Surface Engineering

4.1 Background

The surface of QPF dies is critical for maintaining both formability and surface quality. There are three mechanisms that contribute to die surface degradation: (1) oxidation, (2) lubricant accumulation, and (3) galling or wear.

4.1.1 Oxidation. During QPF, the metallic die and aluminum sheet are not only subjected to the stresses associated with frictional and contact forces, but are also thermodynamically unstable and react with oxygen to form metal oxides, which completely change the characteristics of the tribological system. In addition, the characteristics of the die oxide layer change with the continuous interaction between the surfaces. These changes make forming with newly polished dies different from forming with a tool that has been used to make a large number of panels.

The presence of a thick oxide layer on the die surface may act as a parting agent and help in the reduction or elimination of metal-metal contact (Ref 45, 46). Unfortunately, it is very difficult to maintain a uniform oxide layer on a forming tool. This is illustrated in Fig. 4, which shows a cast iron QPF die after forming a large number of panels. The coloration of the die is irregular, indicating differences in the oxide layer on the surface. The oxide layer on the lighter areas has been removed from the surface due to wear, resulting in newer, thinner oxide layers covering the substrate. It was observed that the areas with thicker oxide layers showed less wear and gave better lubricity.

4.1.2 Lubricant Accumulation. Another factor that can affect the die surface over time is the accumulation of lubricant. Excessive lubricant on radii can lead to sliding and necking, and when accumulated on class A areas of the part, to surface defects that require repair. Class A refers to all exterior surfaces of the vehicle, and, thus, they are required to be of the highest surface quality. Currently, GM uses a CO_2 cleaning system to remove lubricant buildup from the die (Ref 47). While the CO_2 process works well, preventing the accumulation would be the preferred method for avoiding this detrimental change in die surface.

Fig. 4 QPF die used at GM on Oldsmobile Aurora decklid. Oxide layer variation across the tool is observed visually. The lighter regions have a thinner oxide layer and show increased aluminum buildup and galling.

4.1.3 Galling. Galling is a wear process associated with lubricant film breakdown resulting in accumulation of sheet material on the tool surface and subsequent scoring of the workpiece surface (Ref 48-54). In QPF, galling is manifested by the presence of aluminum particles that become attached to the forming tool. Examples of the particles accumulated on a forming tool are shown in Fig. 5. These particles produce scoring on subsequent panels formed on the tool, resulting in surface imperfections that require metal finishing. A cross section of one of the particles is shown in Fig. 6. The “particle” is actually a multilayer of aluminum, aluminum oxide, and boron nitride that accumulate with time. These particles cannot be removed with the previously described CO_2 cleaning system.

4.2 State-of-the-Art

4.2.1 Die Materials. Several types of materials, including cast iron, tool steels, cast aluminum, and ceramics have been used to construct dies for SPF or QPF. General Motors’ experience is that cast irons provide better lubricity than tool steels, but can be difficult to polish to a fine finish, and weld repair can lead to surface imperfections. As a result, P20 tool steel has been chosen as the mainstream tool material for QPF applications at GM. Several researchers (Ref 55-60) have investigated the wear characteristics of alternative tooling materials when using different lubricant types, die surface finishes, contact pressures, sheet metal treatments, and draw speeds during hot forming processes. In some cases, progressive testing has been used to evaluate the evolution of the die materials friction coefficients and wear characteristics during forming (Ref 56, 57). This work indicates that the long-term integrity of the die surface is compromised when using standard die materials without coatings or surface treatments.

4.2.2 Die Coatings. Numerous coatings and surface treatments have been developed and applied to reduce wear and extend the life of metalforming tools (Ref 61-77); however, minimal work has been published in applying these coatings to SPF or QPF dies (Ref 33). Various surface techniques, such as gas nitriding, plasma nitriding, plasma spray, physical vapor deposition (PVD), and chemical vapor deposition (CVD), have

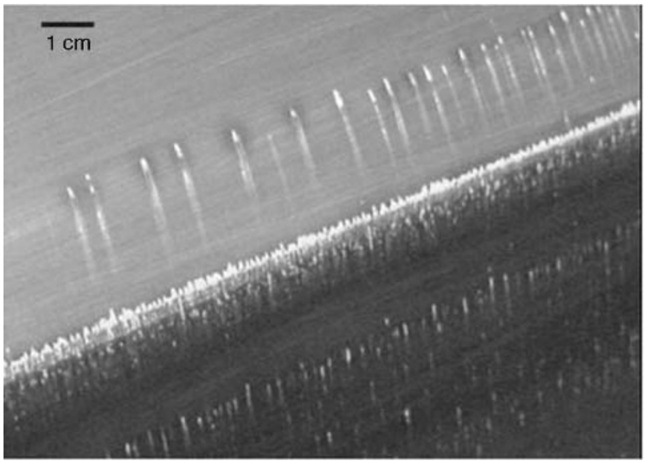

Fig. 5 Aluminum particle buildup on QPF tools

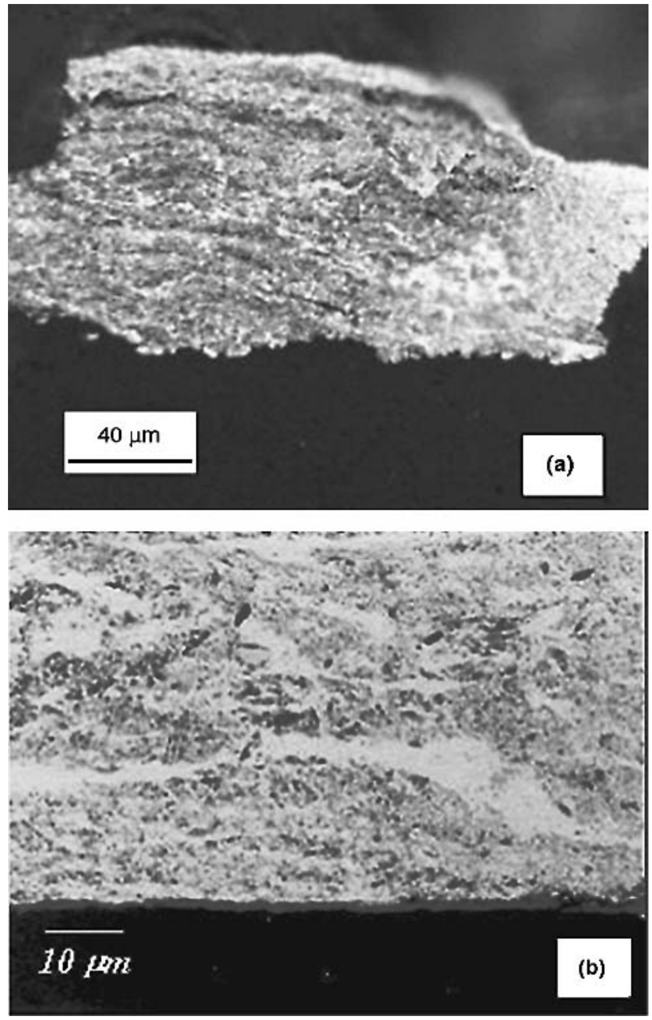

Fig. 6 Layered aluminum particles after removal from QPF die. (a) Macrograph of entire particle showing layered structure. (b) Micrograph of cross section of particle showing layered structure

been successfully used to improve die resistance against wear during hot sheet metal working (Ref 78, 79). Under near production conditions, PVD- and CVD-coated sheet metal working dies show increased durability, as compared with uncoated tool steels (Ref 80-91). Positive results on aluminum die casting molds have been obtained with PVD TiN and CrN, and CrC coatings (Ref 92, 93). CrN coating has also shown a remarkable improvement in the hot extrusion of aluminum (Ref 78, 84, 85, 92, 93) in comparison to other surface technologies, such as plasma nitriding, plasma spraying, and CVD. Additionally, improvements in wear resistance in some hot working processes have been recently obtained with TiN-TiAlN multilayers (Ref 94, 95).

The major advantages of PVD are the almost unlimited variation in the chemical composition of the coating material and the deposition of compounds such as nitrides, carbides, and so forth, and materials such as carbon or diamond. Plasma vapor deposited coatings also replicate the tool substrate, eliminating the need for postcoating surface preparation. Die complexity, size, and weight currently eliminate PVD as a viable alternative for coating QPF production dies.

Many of the coatings described previously have been evaluated at GM R&D under QPF conditions, and the best performers were chosen for prototype scale experiments and further production operations (Ref 33). The current QPF dies for the production of the 2004 Malibu Maxx liftgate are treated with a high-velocity oxyfuel (HVOF) sprayed CrC/NiCr coating (Ref 96). A proprietary process for the preparation of the substrate before coating was used. The surface was also polished after coating to achieve the desired roughness required for the production of exterior components and to ensure a uniform coating thickness. This coating has performed well in service; however, there remain opportunities to improve its performance or identify alternate solutions.

4.3 Research Opportunities

The surface of SPF and QPF dies degrade by oxidation, lubricant accumulation, and galling. While work on die coatings has suggested that these effects may be reduced, a coating has not been identified that completely eliminates these effects. As a result, future research should focus on first improving the fundamental understanding of oxide development, lubricant and aluminum adhesion to substrates, and wear of various substrates at temperatures between 400 and 500 °C.

The production of a self-lubricating oxide coating would be an excellent solution for this problem in QPF tools. In this way, there would be no need for a die surface coating or treatment. An important area of research would be to identify alloying additions to current die materials that may improve the forming surface through formation of a stable, lubricious oxide.

Research is also required to understand the adhesion of aluminum to die materials and coatings under QPF conditions. The ideal coating or die surface would prevent adhesion of aluminum and enable the forming of tens of thousands of panels without interruption. Included in the research could be the development of a test for galling at elevated temperatures, similar to the test already in place for evaluating galling at room temperature (Ref 97).

5. Modeling

5.1 Background

The shift from a low-volume, niche process (SPF) to a higher-volume, automotive process (QPF) has placed a greater importance on the ability to accurately model hot blow forming and determine whether a specific geometry can be successfully formed. Successful modeling enables decreased die tryout. Superplastic forming has been modeled using a variety of techniques including commercial codes such as PAMSTAMP (Ref 98), PAMQPF (Ref 99), MARC (Ref 100-104), ABAQUS (Ref 38-39), DEFORM (Ref 105), METAFOR (Ref 106), and NIKE2D (Ref 107), as well as some numerical analysis (Ref 36, 37, 108). The published work on modeling has treated friction in a variety of ways. Some papers do not address friction at all or only provide the coefficient of friction value (μ) used in the analysis (Ref 100, 101, 103, 105, 109). A number of authors have performed detailed studies to understand the effect of changing the coefficient of friction on the output of the simulation (Ref 36, 37, 106, 110, 111); however, the friction coefficients (μ) used for different conditions varies among the authors. Sliding has been modeled using μ between 0 and 0.3, while sticking has been modeled using μ between 0.3 and ∞. Despite the differences in μ values used, all authors agree that friction plays a critical role in accurately modeling SPF or QPF processes.

5.2 State-of-the-Art

Much of the work on simulation of SPF or QPF has been academic, and it is unclear to what extent the finite element method (FEM) packages are used for designing components in production. The use of design rules-of-thumb is still used for niche applications; however, high-volume QPF applications make extensive use of PAM-QPF to predict formability and ultimately improve the tools to enhance forming. Current analyses assume a constant value of friction across the entire die surface and use a value of approximately 0.3 for μ.

5.3 Research Opportunities

The first opportunity for modeling of friction during QPF or SPF is an accurate representation of the coefficient of friction both in various locations across a die, but also a representation of how the coefficient of friction evolves as the number of panels across the die increases. Once this information is available, the ability to tailor friction across the forming tool must be included in the finite element models to provide more accurate forming simulations. Finally, the finite element simulations should be modified so that they can predict the optimal friction distribution in a QPF or SPF forming tool. This would enable the die surface and lubricant distribution to be controlled in a manner to enhance forming.

6. Summary

The present review of tribological issues in QPF identified a number of areas where additional research and development is required. These areas were divided into four categories: friction testing, lubrication, die surface engineering, and modeling. The areas of research in each category are summarized below.

6.1 Friction Testing

An industry standard test that accurately represents QPF deformation is required. This test must include the ability to significantly stretch the aluminum blank while it is sliding past the representative tooling material.

6.2 Lubrication

Research and development on QPF lubricants should focus on low-cost materials and methods of application. These lubricants should be applied very uniformly, with good adhesion to the blank and should not require special cleaning to remove after forming.

6.3 Die Surface Engineering

A coating or surface treatment is required that can be applied to large dies and does not require surface finishing after application. The coating or treatment should prevent adhesion of aluminum to the die surface, thus preventing galling and panel abrasion. Research is required to understand the phenomena of aluminum adhesion to the die and identify methods to prevent it.

6.4 Modeling

The finite element codes used to model QPF should be modified to incorporate variable friction coefficients across a tool. In addition, the ability to calculate the desired coefficient of friction in various regions of the tool to provide optimal formability would be a tremendous benefit to the engineering of die surfaces.

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