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Characterizing Galling Conditions in Sheet Metal Stamping

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Abstract

Multiple experimental studies were performed on galling intiation for variety of tooling materials, coatings and surface treatments, sheet materials with various surface textures and lubrication. Majority of studies were performed for small number of samples in laboratory conditions. In this paper, the methodology of screening experiment using different combinations of tooling configurations and sheet material in the lab followed by the high volume small scale U-bend performed in the progressive die on the mechanical press is discussed. The experimental study was performed to understand the effect of the interface between the sheet metal and the die surface on sheet metal flow during stamping operations. Aluminum sheet AA5754 2.5mm thick was used in this experimentation. The sheet was tested in laboratory conditions by pulling between two flat insert with controllable clamping force and through the drawbead system with variable radii of the female bead. Comparing pulling forces during sheet metal flow through the testing setup provides information on flow resistance along the interface between the sheet and the tool surfaces. Onset of galling can be detected by the growth of the pulling force. In addition, it is defined by measurement of the surface of the tool and the scratches on the surface of the samples. Typical galling is seen as lines of sheet material deposit on the surface of the die parallel to the sheet material sliding. Most of galling is observed in the areas where lubricant can be forced out of the contact zone, such as edges of the strip, die entry radii or female bead radius.

1. Introduction

Creating consistent forming conditions which would lead to minimal variability in produced sheet metal parts in high volume production is one of the primary goals of manufacturing engineers and researchers specializing in sheet metal forming. Changes occurring on the die surface, such as die wear, galling, inconsistent sheet lubrication, as well as changes in die and press settings represent significant manufacturing problems. Majority of studies addressing these problems are based on experimental work. It should be emphasized that the literature review discussed below tries to emphasize the existing testing methods and recommended approaches to minimize galling. Schedin and Lehtinen [1] discussed the transfer of material between contacting surfaces in sliding systems, which affects friction and wear behavior. The transfer process involves the accumulation of sheet debris on some of the initiation sites, leading to more severe contact stresses. The action of the lubricant mainly delays the transfer process compared to testing without lubrication.

The paper also presents mechanisms for galling in sheet forming operations for both lubricated and unlubricated conditions, demonstrating the influence of tool surface roughness on the galling mechanisms. The materials used were brass as sheet material and a quenched and tempered tool steel as tool material. The lubricant was a naphtenic base oil with additions of 5% oleic acid. The study concludes that the initiation of galling occurs at tool surface defects, which are either produced during the tool surface preparation or during testing when hard fragments cut into the tool surface. The action of the lubricant mainly delays the galling process. The transfer process is sped up without lubrication through a more extensive production of hard sheet fragments and a more rapid build-up of the transfer layer. The paper suggests that the tool surface should be hard and smooth to avoid or delay the transfer process that leads to seizure of the contact. Sato et al. [2] studied the anti-galling performance of a diamond-like carbon (DLC) coated tool. Bending tests of aluminum sheets without lubricant can be successfully performed with the DLC coated tool, but the surface roughness of the bent specimens was increasing significantly.

Hummel and Partlow [3] compared threshold galling results from two broadly used testing methods. The methods employed were the ASTM standard G98 button-on-block test and the button-on-cylinder test. The threshold galling load of three types of stainless steels was determined and compared with literature. The results showed a significant difference in galling results for type 303 stainless steel, which could be attributed to different interpretations of the experimental data. The study suggests the need for a more robust method of calculating the threshold galling load from experimental data. An interesting finding was the decrease in the galling resistance of specimens placed in an oxygen-reduced environment for several days immediately following final surface preparation, indicating that the oxide layer thickness plays an important role in galling prevention. The study concludes that oxidation layer thickness plays a critical role in galling and needs to be studied in more detail. This study indicates that for any combinations of contacting materials, there is variety of factors which can make a significant difference in galling performance.

Podgornik et al. [4] investigated the impact of surface roughness on the galling properties of coated forming tool steel. The study finds that reducing surface topography significantly improves the galling and anti-sticking properties of the tool surface. Therefore, it recommends reducing substrate roughness or polishing the contact surface after coating. The study also finds that a carbon-based low-friction coating reduces the probability of worked material adhesion, even at high surface roughness values and under starved lubrication. Polishing the substrate prior to coating deposition lowers friction and increases the critical load for material transfer. However, post-polishing of a ground and coated surface provides similar or even better galling properties compared to the finest substrate polishing. The study concludes that carbon-based low friction coatings greatly improve the friction and galling properties of forming tool steel, and a DLC coating of the WC/C type may provide excellent protection against the transfer of stainless steel, even under starved lubrication.

Kim et al. [5] presented a study on galling, a form of adhesive wear, in the forming of advanced high strength steel (AHSS) in automotive stamping. The study uses the twist compression test and finite element analysis to differentiate the performance of galvanized coatings and lubricants, understand the fundamental aspects of powdering and galling, and determine the critical interface pressure and temperature that initiate galling or powdering in forming galvanized AHSS. The study finds that galling and powdering become severe as the contact pressure increases, and that lubricant has a major effect on preventing galling and powdering. The study also finds that the tool surface roughness increases with increasing coefficient of friction, resulting in increased sheet surface roughness and more severe galling and powdering. The study concludes that maintaining the tool surface finish within an acceptable range can prevent any ploughing effect of the sharpened asperities of the tool surface on the sheet, thus reducing scoring and galling conditions.

Hou et al. [6] investigated galling through rectangular pan and U-channel stamping experiments. The authors explored the effects of stress states, tool materials, surface treatments, and sheet materials on galling. The paper suggests a combination of hardening, surface polishing, and Cr coating as the optimum tool treatment for forming bare high-strength steel. It also finds that hot-dip galvanized steel shows better galling behaviors than galvannealed and bare steel sheets, with performances improving with increased tool hardness. However, galvannealed steel shows severe galling when the tool hardness is very high.

Lindvall et al. [7] investigated galling, a form of wear causing tool failure in sheet metal forming, using a slider-on-flat surface (SOFS) wear tester. The study examined how changes from elliptical to line contact geometry influence galling initiation under dry sliding, testing a micro clean tool steel against ferritic low-strength and martensitic high-strength steel sheets. The research finds that elliptical contact causes galling quicker than line contact, and that contact pressure is a significant parameter in the SOFS wear tester. Lower contact pressure results in a longer sliding distance before galling onset. The study also revealed that galling is detected for all tool geometries, regardless of whether the sheet experienced bulk plasticizing or not, and that the high-strength Docol 1200M sheet exhibits a larger dependence on tool geometry compared to the softer DC01 sheet. The paper concluded that contact pressures typical for most common industrial applications can be successfully simulated by selecting tool geometry and normal load in the SOFS tester.

Shanbhag et al. [8] used force and acoustic emission sensors to study galling behavior using scratch tests performed at different depths of penetration and sliding distances. The study used force and acoustic emission sensors to study galling behavior, correlating these with profilometry wear measurement features. The research identified non-galling conditions, characterized by only ploughing wear, were observed for smaller values of depth of penetration, while galling was observed for larger values of depth penetration. The authors indicated that transition from non-galling to galling conditions, marked by the abrasive cutting wear mode, can be actively monitored by studying the initiation of unstable force and the presence of acoustic emission burst signals.

De Argandoña et al. [9] investigated the impact of surface roughness on the coefficient of friction and the viability and geometry of components in aluminum forming processes. The paper investigates the impact of surface roughness on the coefficient of friction and the viability and geometry of components in aluminum forming processes. It uses strip drawing tests on 1050 aluminum alloy textured under different conditions to generate a variety of surface roughness and calculates the coefficient of friction based on contact pressure. The study finds that a sheet surface roughness of about 1 micrometer offers the lowest coefficient of friction when working with forming tools with a surface roughness of 0.2 micrometers. The paper also analyzes the effect of surface texturing on the drawability of the material and the final geometry of components, finding that 'low texturing' condition offers the highest safety in the component drawing operation.

Dohda et al. [10] provided a comprehensive review of galling phenomena in metal forming examining different galling conditions in sheet and bulk metal forming processes, their evolution, and the effects of temperature. The authors presented various anti-galling methods employed to prevent or delay galling defects, including improving the lubricant properties, coating the workpiece, and using coated tools. The paper introduces techniques for quantitatively measuring galling and presents related prediction models, including friction, wear, and galling growth models. The paper concludes by suggesting future research directions, including the development of high-resolution quantitative measurement technologies, the creation of improved galling models related to heat, and the importance of interfacial temperature measurement techniques.

Shih et al. [11] explored the factors contributing to die wear and galling in stamping DP980 steels during die tryout and production processes. The study found that insufficient die surface hardness is a significant factor leading to die wear and galling. It recommends the use of D2 tool steel with a hardness of 60 HRC for non-coated die tryouts. Additionally, the paper discusses the potential use of newly developed dry lubricants to prevent die wear and galling in non-coated die tryouts with DP980 steel. The surface roughness of cold-roll DP980 steel is found to be proportional to the friction coefficient in non-coated die tryouts. Furthermore, cold-roll bare DP980 steel exhibits higher friction, galling, and die wear characteristics compared to coated DP980 steel in both non-coated die tryout and production conditions. The paper also examined the performance of GI-coated DP980 steel when tested with a CrN die. It noted that GI-coated DP980 steel tends to have significant build-up, which can be prevented with pre-phosphate coating. Pre-phosphate coating is observed to reduce friction and prevent die wear and galling in stamping DP980 steels. The hardness of the die material is a key factor influencing galling and wear in the die tryout phase. The paper suggests that using better surface-treated die materials and implementing anti-galling strategies can help reduce galling and wear in both die tryout and production processes.

Moghadam et al. [12] presented a comprehensive methodology for evaluating critical die features in sheet metal forming dies to understand wear behavior. The study focuses on a 3D scanned industrial tool used in sheet metal forming and employs finite element simulation software to analyze drawing in, normal pressures, and die wear. Three drawbead scenarios are compared: no drawbead, a drawbead with a constant radius equal to the sheet thickness, and an optimized drawbead geometry. The simulation identifies critical wear zones along the die shoulder and the stepped drawbead. These zones are then tested offline to evaluate different tribosystems. The study finds that only a hazardous, chlorinated lubricant enables stable production with an uncoated tool steel for the specific production platform. However, it suggests that the Tenifer QPQ surface treatment combined with different forming oils could provided an environmentally friendly alternative.

Based on reviewed studies, it should be indicated that variety of testing methods are employed by researchers to understand the effects of various factors on galling. Keeping in mind a very large number of possible combinations of sheet materials with or without coating, different surface textures and roughness, variety of die materials with possible coating variants and surface roughness values, variety of lubricants, different sliding speeds, contact pressures and temperatures, it becomes clear that precise prediction of galling by analytical or numerical methods is nearly impossible. In addition, it should be admitted that in majority of studies described above, testing was done in relatively slow modes with rather limited number of forming cycles. Also, in production conditions, thousands, tens of thousands or even hundreds of thousands of stamping cycles can modify the die surface, wear out coating or nitrided layer and lead to galling.

It is also obvious that having a universal table of practical recommendations for all possible scenarios is nearly impossible as well. Testing of different cases in production provides exact manufacturing conditions compared to laboratory methods mentioned above. However, this approach is very expensive due to the necessity to rework the production die surface. It also should be admitted that changes in friction conditions lead to variability in restraining forces of the binder system of the die, which may lead to dimensional deviations of stamped parts and possible scrapping significant amounts of produced parts.

The hybrid approach proposed in this study includes initial screening experiments sorting out the combinations of die material, die surface conditions, sheet material, lubrication and level of contact stresses, which lead to nearly immediate changes in forming conditions, typically involving galling and die surface degradation. During these initial screenings, the lab experiments are performed with precision measurements of pulling forces, loads on different elements of the die, amount of lubrication on the sheet surface, changes in the roughness of the sheet while passing through the experimental die, changes in the amount of lubrication as a result of forming, and usually rather small amounts of sheet metal deposits on the die surface. These measurements, at the moment, are very difficult to achieve in real manufacturing conditions. All these measurements are very useful from the perspective of understanding of what is happening on the interface between the sheet and the die. But they can be performed only for rather limited numbers of tests and are not able to capture the effects which might take place after thousands or tens of thousands of stamping cycles. Therefore, for configurations which pass the initial screening lab experiments, high volume small scale testing in near production conditions, for example using U-bend geometry, can be a very cost efficient method, which reveals early to mid-stage production problems appearing after thousands or even tens of thousands of stamping cycles. This study should be performed before full scale production dies are fabricated.

A combination of two stage approach of initial screening and then testing in high volume small scale can be advanced even further if the small scale die inserts return to the lab after tens of thousands of stamping cycles, and their performance is remeasured with laboratory precision (for example after stamping of 50,000 of U-channel coupons) reproducing the identical amount of lubricant on the surface and the same sheet material. Comparison of pulling forces as well as the residual amount of lubrication after testing for the new insert and the same insert after 50,000 strokes has potential of providing more fundamental understanding of the sheet metal flow in realistic production conditions.

2. Methodology of measuring efficiency of the interface between the sheet and the die during laboratory screening tests

Characterizing of the interface between the sheet and the die involves multiple aspects, such as the roughness of the sheet, potential coating on the sheet, roughness of the die surface, die material, die coating or surface treatment, type of lubrication and the thickness of its layer, compatibility between the die and sheet materials. Comparison between different interface configurations can be quantified by the pulling force needed to move the sheet along the die surface. This force might involve either a combination of forces needed for plastic deformation of the sheet and friction forces, as it happens in drawbead testing method or drawing the sheet through the die entry radius, or directly measured friction force, such as pulling the strip of sheet metal between two flat inserts clamped together.

Comparison of pulling forces while varying just one factor at a time allows direct comparison of lubrications, coatings, and surface treatments for a given configuration of the tool and helps to find overall more efficient interface. Having less friction in sheet metal stamping enables deeper drawing and often usage of higher strength or lighter materials. Also, lower friction forces very likely results in smaller flash temperature at the contact and smaller forces deforming asperities on the surface of the sheet. Significant deformation of asperities might lead to breakage of oxides and protective films resulting in cold welding of sheet metal particles to the die surface, typically considered as galling.

Both configurations of laboratory testing involving: a) only friction forces on the interface between the sheet and the die and b)friction mixed with plastic deformation of the sheet will be discussed below.

2.1. Experimental characterization of sheet-die interface clamping the sheet between two flat inserts

The schematic of the tooling configuration with flat inserts is shown in Fig. 1 and the inserts design can be found in publications [13, 14, 15]. The inserts are clamped with horizontal hydraulic press installed inside the tensile testing frame Instron 5982 with the maximum force of 100kN(Fig. 2). The hydraulic press is mounted on a custom steel table necessary for this setup. The clamping force is adjusted by the pressure in the hydraulic cylinder. Two different horizontal hydraulic presses are used in the experimental work depending on tested material: with maximum clamping force of 78 kN and 280kN. The alignment of the horizontal hydraulic press is provided by four guiding columns. Detailed results on detecting galling onset using this method can be found in [13, 14, 15].

The advantage of this testing method is that any changes on the interface between the sheet and the die is very easy to detect: the changes in the pulling force will instantly reflect the changes on the interface. This testing method is more applicable to drawing of elongated parts without drawbeads, for example rather thick gauge, rail type, structural components. Lubricant on the flange of the deformed sheet in this configuration is trapped between two near flat surfaces and can be squeezed out only in the areas adjacent to the edge of the contact zone. This is more favorable configuration from the perspective of galling avoidance. As described

FIGURE 1 The schematic of the tooling configuration with flat inserts.

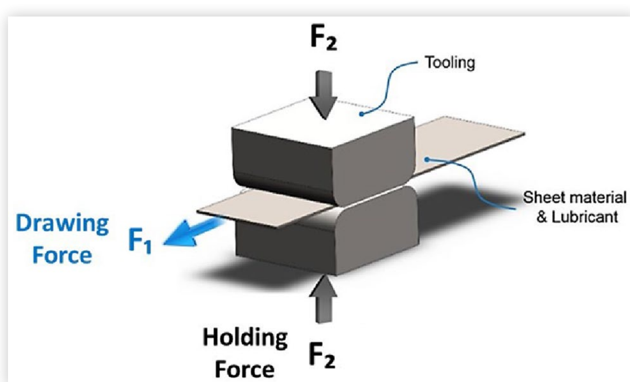


FIGURE 2 The laboratory testing setup: the sheet metal strip is pulled in between the flat inserts clamped by horizontal hydraulic press.

in the Introduction, the galling threshold is the function of specific conditions including roughness of the insert, chemical composition of the insert surface, the type of lubricant and the amount of lubrication on the surface, the surface texture of the sheet, etc. The threshold is defined by increasing of the clamping force in the experimental setup and measuring the pulling force as well as by measuring the surface of the die for potential deposits. This experimentation can define specific galling limit for the configuration of interest. The examples of pulling forces measured as a function of the displacement of the strip in between the grips are illustrated in Figure 3: the inserts were made from D2 tool steel with no coating applied, and 61 AUS lubricant was applied. The green curve illustrates the stable condition with no galling taking place. The red curve illustrates the galling onset defined for this particular configuration: the pulling force is quickly increasing.

Examples of galling occurring on the surface of tested inserts are illustrated in Figure 4. More typical galling origination is in Figure 4a, where it occurs near the edges of the contact zone due to the lubrication being forced out of the contact zone. More aggressive galling condition is illustrated in Figure 4b where galling takes place at

FIGURE 3 Pulling force measured for stable interface (green curve) and unstable interface where galling originates on the die surface (red curve).

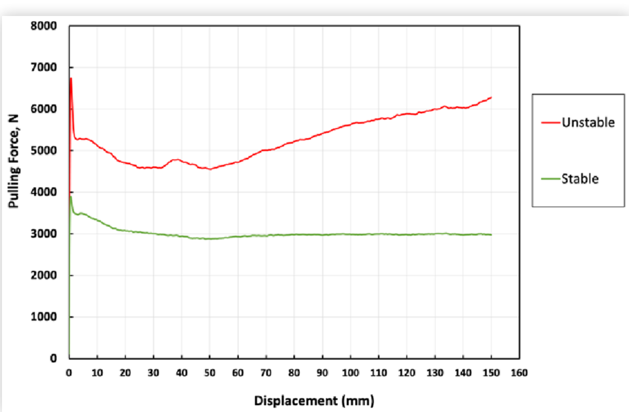
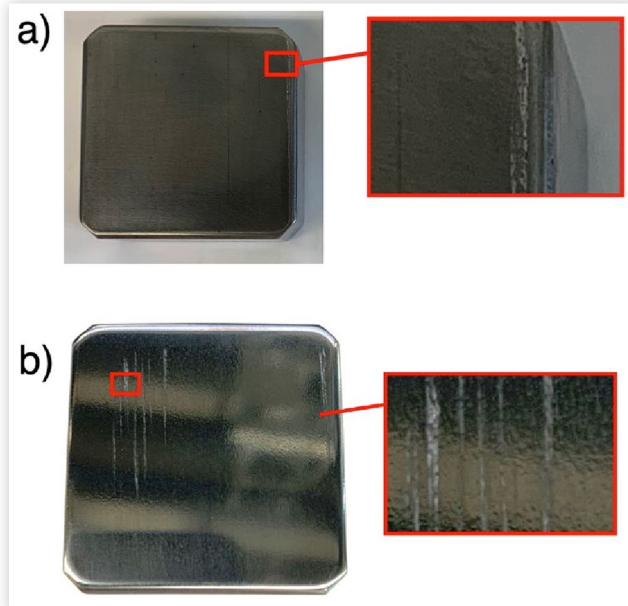


FIGURE 4 Tested insert with galling originating on the edges of the strip (a) and in multiple locations (b).



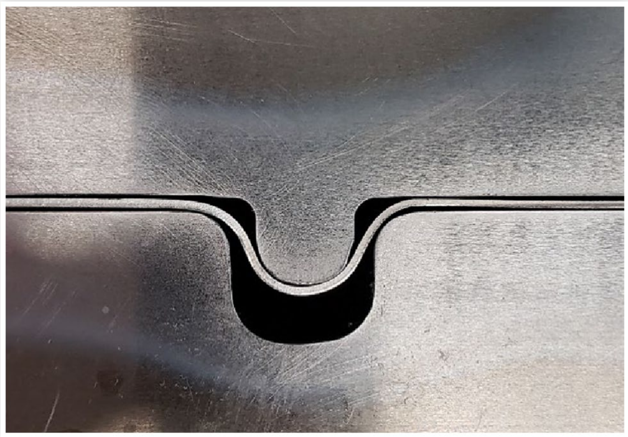
multiple locations including the areas in the interior portions of the contact zone.

2.2. Experimental characterization of sheet-die interface where sheet flows through the drawbead system

Drawbeads are being used in stamping of sheet metal for nearly 100 years. They were still not used in industry in 1915 [16], but were already used in 1932, as indicated by Crane [17] and in all later reference literature on sheet metal stamping. A significant advantage of drawbeads compared to flat binder is that they require significantly smaller binder force to create the same restraining force due to three pairs of stretch bending-unbending taking place while sheet is flowing through the drawbead. Friction forces acting between the sheet and male and female beads contribute to the restraining force as well. The illustration of sheet metal deformation inside the drawbeads is provided in Figure 5.

Since force required for bending-undending rather significantly depends on the radii, the pulling force can be adjusted by changing the radii of the male and female beads. However, the limiting factor for this adjustment is whether the sheet is flowing exactly along the drawbead geometry. Making the radii sharper typically increases the contact pressure between the sheet and the die creating more opportunities for the lubricant to be squeezed out from the sheet surface and create dry contact conditions typically leading to galling. In order to study the onset of galling as a function of the radius of the drawbead, a set of experiments was performed where only one factor was varied: the female radius

FIGURE 5 An example of drawbead system where sheet goes through cycles of bending and unbending [18].



where sheet is leaving the drawbead. The reason for selecting this radius was that it typically has highest level of contact pressure [18]. Typical experimental curves received with lower and higher bead penetration leading to changes in the contact pressure [18] are shown in Figure 6: green curve illustrated the condition in which no galling takes place, and sheet metal flow is stable; red curve illustrates initiation of galling during the test. In this experimentation, the inserts were fabricated from S0050A cast steel. The surface of the insert was plasma nitrided and then hard chromed. 61AUS lubricant was applied in the amount of 0.5g/m^2 measured by NG2 oil sensor. The radius of the female bead was 6mm.

Examples of galling observed during testing 2.5mm AA5754 sheet with 1.5mm and 6mm radii are illustrated in Figure 7. For some die materials [13, 14, 15], galling accumulation during small number of laboratory tests can be rather minimal. However, pulling force increase usually gives a visible indication of galling onset during the test.

FIGURE 6 Illustration of pulling force for stable (green curve) and unstable (red curve) sheet-die interface while sheet material is flowing through the drawbead.

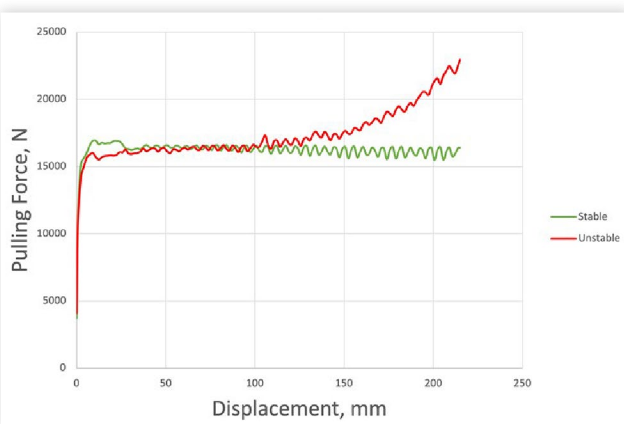
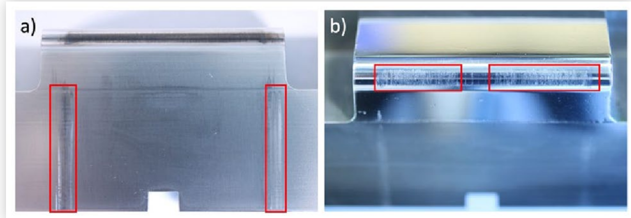


FIGURE 7 Tested insert with galling originating on the edges of the strip (a) and on the radius (b).



3. Methodology of measuring efficiency of the interface between the sheet and the die during high volume small scale stamping tests

High volume small scale test was developed based upon U-bend coupon fabrication described in [19]. The coupon is fabricated using the progressive die, where the sides of the U-bend coupon are initially blanked with only small residual tabs left to transfer the part within the progressive die. During the final operation, the tabs are sheared off, and the U-bend shape is drawn with binder forces applied, as it is illustrated in Fig. 8. The contact pressure between the sheet and the die in the flange area is adjustable by applying different levels of pressure in the nitrogen cylinders which are providing the binder force. The contact pressure can be also adjusted by modifying the area of the binder: reduction in contact zone leads to increased pressure. These two methods of contact pressure adjustment allow wider range of contact pressure typically limited by the configuration when the material of the strip is not flowing into the die cavity anymore.

Examples of tested samples are illustrated in Fig. 9: the sample with no sign of galling is shown in Fig 9a; rather severe galling is illustrated in Figure 9b; ploughing condition is shown in Figure 9c, where the scratches on

FIGURE 8 Schematic of U-bend stamping process.

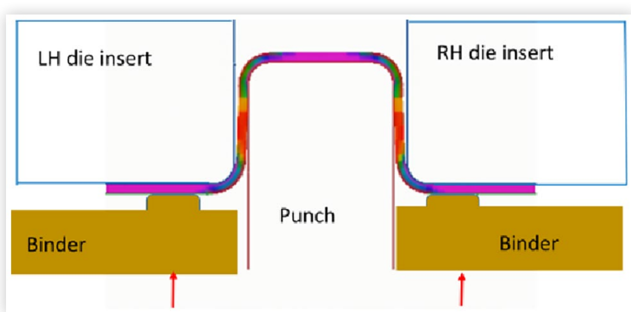
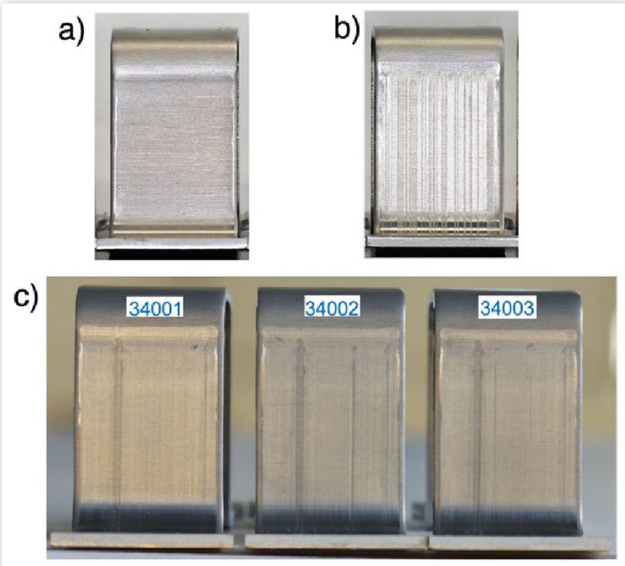


FIGURE 9 Stamped U-bend parts with clean surface (a) and with scratches indicating ploughing and initiation of galling (b), example of unstable galling/ploughing which comes and goes (c).



the surface of the coupon show some inconsistency. Three consequent parts collected after 34,000 tests show that the right scratch appeared on the sample 34,002, while it was hardly seen on the sample 34,001 and was rather minimal for the sample 34,003.

Illustration of deposits of aluminum on the die surface is provided in Figure 10. Areas of deposit can be seen at locations where the edges of the strip slide on the surface of the flange and also at the entrance to the radius, where a peak of contact pressure is usually observed [18]. Deposits on the radius of the die usually result in scratches along the vertical wall of the stamped U-bend coupon.

Examples of U-bent samples stamped from 1mm thick DP980 coil are illustrated in Figure 11. A severe galling condition occurred on the binder surface (Fig. 11a) within several stamping cycles. The increase in friction in the flange area resulted in fracture of the U-bend samples at the die entry zone. Galling prevented material flow into the cavity and led to fracture of the samples illustrated in Fig. 11b. This configuration should have been detected during the screening test following the methodology in the section 2.1. This experimentation led to the idea of necessity of screening experiments with low cost inserts and minimal effort preparation before any further testing is done. The same part geometry in case of 1mm thick DP980 bare sheet material resulted in immediate galling, while for Aluminum galling accumulation for this part geometry was gradual.

FIGURE 10 Tested inserts with galling originating on the edges of the strip and on the die entry radius.

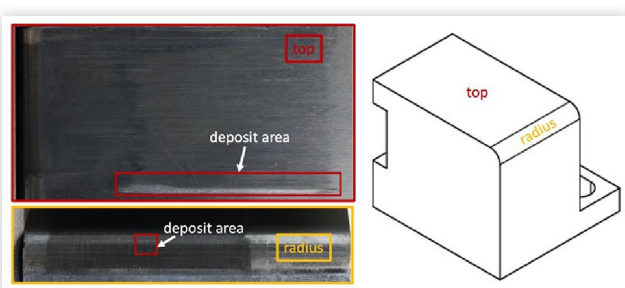
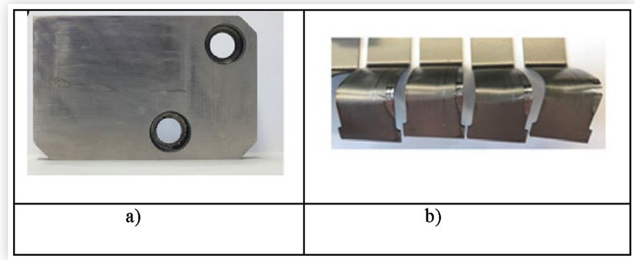


FIGURE 11 Illustration of galling appearing for DP980 experimentation on the binder, which had no coating (a) and fractured sample due to significantly increased friction (b).



4. Methodology of measuring efficiency of the interface between the sheet and the die for the inserts tested in high volume stamping

The approach of small scale high volume experimentation on the mechanical press by stamping multiple parts from the coil in progressive die can't provide full details of experimentation, such as experiment in 2.1 and 2.2. Measured forces from the press are capturing both cutting and drawing processes simultaneously. Also, forces on other elements of the die, such as the binder, pilots of the progressive die, friction forces in the guiding columns of the die all add together. A potential solution is in introduction of die sensors which are currently under development. A simpler solution is in developing fixtures where inserts of the progressive die can be tested in the lab similar to the methodologies explained in sections 2.1 and 2.2. A schematic of such a fixture is illustrated in Figure 12. A U-bend insert shown in red is positioned inside the laboratory horizontal hydraulic press with the binder and the punch constructed in a similar fashion as in the progressive die. The major difference is that the sheet is pulled by the grip rather than by the punch, as shown by the blue arrow. This pulling force can be accurately measured.

The graphs in Fig. 13 show two cases, as in previous testing configuration: green curve shows no galling while

FIGURE 12 Schematic of the laboratory setup of testing interface efficiency for U-bend inserts after high volume number of stamping cycles.

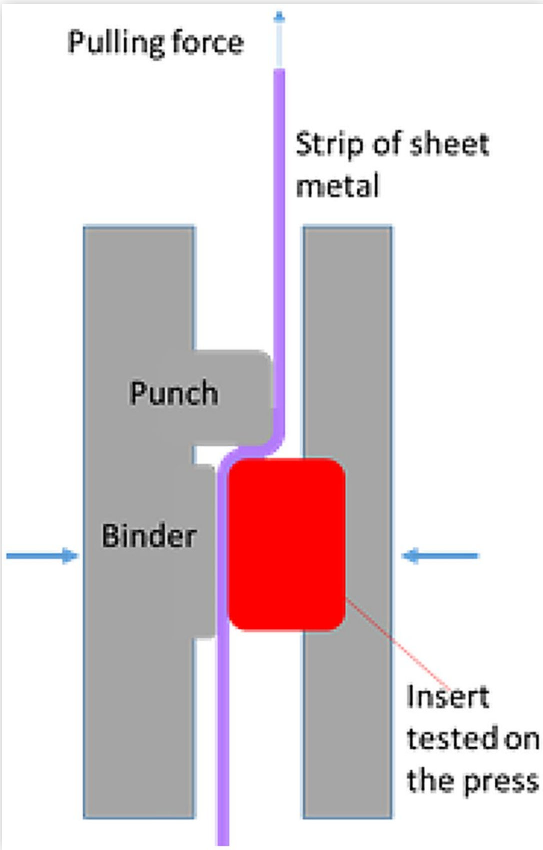
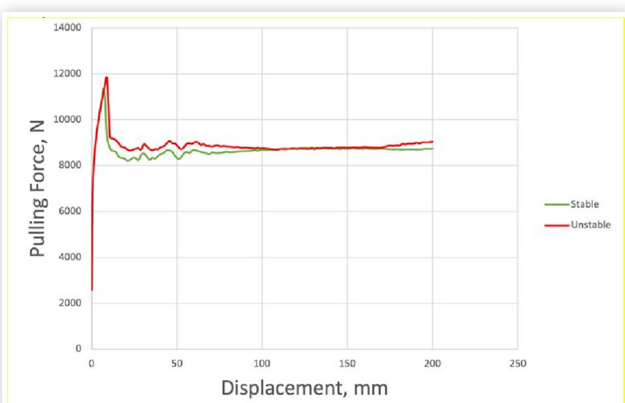


FIGURE 13 Illustration of pulling force for stable (green curve) and unstable (red curve) sheet-die interface while sheet material is flowing through the U-bend tool.



red curve shows some galling initiation. The difference in force values is rather small due to other factors such as sheet bending and unbending while flowing through the die entry and the punch radius. The tested inserts were fabricated from D2 tool steel with DLC coating on the surface and 0.5g/m^2 of 61AUS lubricant applied. A 2.5 mm thick aluminum sample of the 5754 alloy was tested in this configuration, as illustrated in Fig. 14. The test revealed

FIGURE 14 Examples of samples after pulling through the U-bend insert in configuration of Fig. 12.

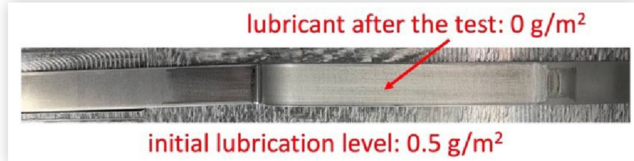
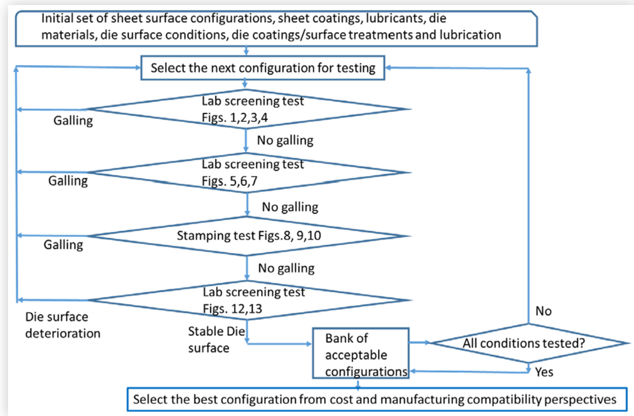


FIGURE 15 Method for identifying galling.



a lack of lubrication in the area that went through the flat binder and then bending-unbending at die entry radius.

5. Summary/Conclusions

In this paper, the hybrid method is introduced to test potential galling conditions and avoid them in production environment. The methodology includes testing between two flat inserts with controllable clamping force similar to material flow through the flange in tooling configurations with no drawbeads. It also includes testing galling conditions in the drawbead system to define the appropriate radius were galling would not occur. It also includes high volume small scale U-bend performed in the progressive die on the mechanical press. This hybrid approach allows to screen the configurations in which galling occurs at the early stage of testing, while more intense effort is dedicated for the configurations where galling might happen after thousands or even tens of thousands of tests. The galling determination methodology outlined in Fig. 15. The flowchart begins with an initial set of parameters including sheet surface configurations, sheet coatings, lubricants, die materials, die surface conditions, die coatings/surface treatments, and lubrication. The next step is to select the configuration for testing. Three type of tests are shown for different scenarios where galling is tested through:

- Lab screening test clamping the sheet between two flat inserts illustrated in Figs. 1,2,3,4 leading to either occurrence or non-occurrence of galling. Galling is detected from the force-displacement curves, from the scratches on the formed part surface, and from measurements of the surface roughness of the die inserts. In case of no galling, the study continues to the next test.

- Another lab screening test where the sheet flows through the drawbead system is shown in Figs. 5,6,7 again leading to either occurrence or non-occurrence of galling. In case of no galling, the study continues to the next test.
- Stamping test where die tested in high volume stamping is presented in Figs. 8, 9, 10.

If there's no galling in all three types of tests it proceeds to another "Lab screening test" (Figs. 12, 13) where efficiency of the interface between the sheet and the die for the inserts previously tested in high volume stamping is measured based upon force-displacement measurements and analysis of surface roughness of the die insert. If no major surface deterioration is detected, this configuration gets to the bank of acceptable stamping conditions. This algorithm continues until all potential configurations are tested. The flowchart ends with the selection of the best configuration from both cost and manufacturing compatibility perspectives. This systematic process allows to identify the best sheet surface configurations, coatings, lubricants, and stamping die conditions. It involves multiple steps of lab screening and stamping tests to determine if galling occurs in the early stage or later during the life of the stamping die.

Comparing pulling forces during sheet metal flow through the testing setup provides information on flow resistance along the interface between the sheet and the tool surfaces. Onset of galling can be detected by the growth of the pulling force. Most of galling is observed in the areas where lubricant can be forced out of the contact zone, such as edges of the strip, die entry radii or female bead radius.

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