Assessment of solutions to reduce wear with the warm forming of aluminum

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Abstract. Aluminum warm forming can be used to form very hard sheet materials and reduce the weight of the parts produced, helping to lighten cars. While many studies have focused on the aluminum warm forming technique, few examine the effects of temperature on sheet - tool contact conditions during repetitive parts making. The purpose of this study is to focus on the different sheet/tool contact configurations with the warm forming of aluminum based on 2 types of tests: tribological testing for an initial range of contact configurations and press testing of the forming tool for the final evaluation of a range of configurations. 18 configurations, involving various materials, tool coatings and lubricants, were initially evaluated using a warm pin test on an AWS5083 H111 sheet. According to the analysis of wear surfaces, adhesion/galling type damage occurred on pins and highlights the importance of lubricating with a beneficial influence of tool coatings. The analysis of the coefficient of friction alone cannot explain the degraded aspect of the pins obtained. Then press tests with a tunnel-shaped part were carried out on 4 selected configurations. If the coated and lubricated configurations are satisfactory, the uncoated and lubricated configurations are surprisingly good and better than the tribological results have shown. In addition to the risks of pick-up and galling, the deposits of residues on the tool are compared for the lubricants tested.

1. Introduction

Warm forming of aluminum is one of the sheet metal forming processes that are able to provide high-performance solutions to reduce the weight of motor vehicles. The studies conducted on warm forming mainly focus on the performance of the process (formability, quality, weight reduction, strength, productivity) [1], [2], [3], [4] but few of them focus on tool life [5]. Aluminum is already well known for the risks of galling it can produce with the blanking or drawing tools, but it poses an additional risk regarding this type of damage when it is worked at a high temperature (figure 1). Therefore, in addition to studies focusing on the performance of the process, studying the wear resistance of the tools appears to be important too.

The objective of this study is to understand the adhesion and galling phenomena which occur at the sheet/tool contact area during warm forming of aluminum and to determine contact configurations that will ensure a good level of performance. This study is comprised of two stages: first, an assessment of a large group of sheet/tool contact configurations through tribological testing and, second, an assessment of selected contact configurations through press drawing testing.
2. Experimental aspects

2.1. Processed sheet material
We selected a 0.8mm thick AW-5083 H111 (EN 485-2) aluminum alloy. This type of aluminum alloy is particularly suitable for warm forming [6]. For this alloy, the most appropriate temperature for warm forming seems to be located around the value of 180°C (Table 1 [4]).

Table 1. Mechanical characteristics of AW-5083 H111 at various temperatures. A, n and r are respectively elongation, strain hardening exponent and plastic strain ratio.

|       | Rm (MPa) | Rp0.2 (MPa) | As0 (%) | n from 6% | r at 9% |
|-------|----------|-------------|---------|-----------|---------|
| RT    |          |             |         |           |         |
| 45    | 313      | 164         | 18.6    | 0.27      | 0.56    |
| 90    | 302      | 154         | 18.6    | 0.28      | 0.81    |
| 180°C |          |             |         |           |         |
| 45    | 203      | 150         | 74.8    | 0.14      | 0.50    |
| 90    | 192      | 138         | /       | 0.14      | 0.65    |

For our tests, we used a temperature of 180°C.

2.2. Tribometer tests
The first assessment of different contact configurations was carried out using a “Pin-Test” tribometer [7] suitable for pin/sheet friction (figure 2).
Sliding is generated by the translational motion of the pin against the flat surface of the sheet, the latter being secured to a dynamometer table. A three-dimensional force sensor transmits the stresses of the pin against the opposite surface. A heat pad is placed below the sheet to warm it up by conduction and a ceramic heat shield provides heat insulation between the sheet and the machine’s frame. The temperature is controlled with a PID controller.

18 configurations were tested with the parameters described in table 2. Lubricants and coatings are commercial products.

Table 2. Parameters of the configurations tested during the tribological tests.

| Sheet | Tool | Lubricants | Surface characteristics | Test temperature (°C) |
|-------|------|------------|-------------------------|-----------------------|
| AW 5083-O t= 0.8 mm | X153 CrMo V12 | GRA 702 | M EP 65 CF | M AL 150 | O WD (18%) | A68 WG2 | IN15 14/2 | No coating CrN + a -C:H | Data Graphite Grease based Oil based Oil based Water based Oil based Coatings |
|       |      |            |                        | 1          | 2         | 3         | 4         | 5          | 6          | 1         | 2         |
|       |      |            |                        | 175        | 200       |

The test conditions were as follows: temperature of the sheet equal to 180°C, normal force equal to 10 N (maximum pressure = 1000 MPa), sliding velocity equal to 20 mm/s, sliding length equal to 110 mm, 5 rubbed lengths on 5 different marks. The tribometer test is designed to reproduce tribological conditions of aluminum warm forming process with similar sliding speed, and temperature. The contact pressure of tribometer test is much higher than that of the process, because of limit of contact geometry of the tribometer. This higher pressure is hoped to generate more severe damage to predict the worst case of the process with high pressure pic.

We used two types of criteria to assess the behavior of the sheet/tool interface: examination and analysis of the surfaces of the pin and measurement of the Coulomb friction coefficient.

2.3. Press tests

The manufactured part is illustrated on figure 3. It is a tunnel-shaped part composed of a portion under blank holder and a portion formed by the radius of the die (straight wall) (figure 4).
Figure 3. Shape of the channel part.  
Figure 4. Punch, die and blank holder.

The part was made with a progressive die (figure 5) in accordance with the forming process presented on figure 6. The tests were carried out with a mechanical press at a rate of 30 strokes per minute.

Figure 5. Progressive die tested on the press.  
Figure 6. Strip layout developed for the progressive die.

The test conditions were as follows: temperature of the strip increased to 180°C before forming, strip lubricated on its top and bottom faces at tool inlet (10 g/m² and per face). As the blank holder force was constant, its pressure varied from 1.1 MPa (at the beginning of the forming operation) to 2.5 MPa (at the end of the forming operation).

The criteria for the assessment of the performance of the tested solutions were based on the examination of the tools (blank holders and die radius) and the parts (portion below the blank holder and rubbing portion over the die radius): presence of marks, scratches or pick-up. Regarding the blank holder, another criterion was taken into account, namely the presence and quantity of residues left by the lubricant (residues matter).

3. Results

3.1. Tribological tests

The reference configuration (bare punch without lubricant) exhibited the most significant damage, with a very rapid galling of the punch (figure 7). With the use of a lubricant, the wear resistance of the pin was immediately improved (figure 8) and, in configurations with the combined use of a lubricant and a coating, the surface of the pin exhibited almost no alteration (figure 9) and featured the best wear resistance.
Figure 7. Significant degradation of the pin without lubricant (X153).

Figure 8. Very light degradation of the pin with lubricant (IN1514-2).

Figure 9. No degradation of the pin with lubricant and coating (IN1514-2 - CrN + a-C: h).

The examination of the surfaces of the pins is summarized in Table 3. The lubricants gave very similar results that are difficult to distinguish from one another. Amongst the coatings, CrN + a-C: h seems to be slightly better.

Table 3. Summary of the examination of the pins after the tribological tests.

| Test configuration | X153 | X153 / CrN + a-C: h | X153 / ta-C |
|--------------------|------|---------------------|-------------|
| GRA 702            | Surface with incipient abrasion / adhesion. | Light marks. Incipient abrasion / adhesion. | Light marks. Incipient abrasion / adhesion. |
| M EP 65 CF         | Surface with incipient abrasion / adhesion. | Light signs of chipping | Light marks. Incipient abrasion / adhesion. |
| M AL 150           | Surface with incipient abrasion / adhesion. | No significant damage. | Light marks. Incipient abrasion / adhesion. |
| IN1514-2           | Surface with incipient abrasion / adhesion. | No significant damage. | Light marks. Incipient abrasion / adhesion. |
| A68WG2             | Surface with incipient abrasion / adhesion. | No significant damage. | Light marks. Incipient abrasion / adhesion. |
| O WD (13%)         | Surface with incipient abrasion / adhesion. | No significant damage. | Light marks. Incipient abrasion and adhesion. |

Reference – X153CrMoV12 (dry friction): Significant adhesion and galling

Figure 10 shows the values of the average friction coefficients corresponding to the tested configurations. The friction coefficient values are lower with the bare punch in almost 4 out of 6 configurations. Only the O WD (13%) configuration features a higher value. This result is different from the result obtained after the examination of the pins, where the configurations with coating appeared to be better. As the contact geometry is the same for all configurations, the differences in the friction coefficients certainly result from the interactions between the lubricant and the type of pin, with or without coating, in a boundary lubrication regime. The behavior with the M AL 150, M EP 65 CF and A68WG2 lubricants could very likely correspond to the case where the additives of the lubricant would react well with the pin and generate lubricant products, whereas the behavior with the O WD (13%) lubricant rather shows a favorable effect of water with the two amorphous carbon-based deposits. The GRA 702 case certainly results from the dominant effect of graphite, as this material is not susceptible to the reactivity of the pins with or without coating.
3.2. Press tests
Four configurations were selected for these tests. They are presented in table 4. While the coatings were selected based on the tribological tests, the bare punch was chosen as a reference and industrial solution (less expensive) and the lubricants were selected for the low quantity of residues left on the sheet (IN1514) and the low friction coefficient (O WD 13%). The first oil is a neat oil, the second oil being a water-soluble oil.

Table 4. Configurations tested for the press tests.

| Material / surface coating | Lubricant       | Configuration |
|----------------------------|-----------------|---------------|
| X153CrMoV12 (without coating) | IN 1514         | 1             |
|                            | O WD (13%)      | 2             |
| X153CrMoV12 / CrN + a-C:H | IN 1514         | 3             |
|                            | O WD (13%)      | 4             |

The various types of surfaces obtained are presented on figures 11 to 16. Friction marks that could not be felt by touch were found on both the part and the tool. Scratches could be found on the portion of the part located below the blank holder. Pick-up marks could be found on the tool (blank holder and die radius). Some lubricant residue was also visible.

The summary of the results obtained is presented in table 5.
The configurations without coating (1 and 2) showed a high level of performance and even turned out to be better on the tool as they prevented the occurrence of pick-up. The latter feature departs from the results of the tribological tests, where the risks of pick-up were reduced by the presence of coating. Such a difference in the results may be the consequence of the choices made for the tribological tests, namely a very high pressure and a limited number of marks. In particular, the pressure applied onto the die radius of the press tool is approximately 10 times lower than the pressure applied during the tribological tests.
With regard to the press tests, the presence of a coating on the tool seems to reduce (and even prevent) the deposition of lubricant residues. Even without coating, these residues are significantly reduced in the tested configurations in comparison to the residues found during the previous tests [4]. The various types of tested lubricants seem to have significantly improved this point. The O WD (13%) soluble oil even resulted in a total absence of residues. Nevertheless, its transformation into a powder after the forming operation seems to indicate a degradation which, with the presence of water in its initial formulation, may lead to risks of corrosion [5].

Table 5. Summary of the examination of the parts and tools after the press tests.

| Test config. | Part | Tool |
|--------------|------|------|
|              | Portion rubbing against the die radius | Portion below the blank holder | Blank holder | Die radius |
| 1            | No significant damage. Presence of friction marks which cannot be felt by touch. | No marks or scratches. | Small quantity of lubricant residues outside the area in contact with the sheet. | No pick-up. |
2

No significant damage. Presence of friction marks which cannot be felt by touch.

Scratches and pronounced marks.

No lubricant residues.

No pick-up.

3

No significant damage. Presence of friction marks which cannot be felt by touch.

No marks or scratches.

Pick-up. No lubricant residues.

No pick-up.

4

Light degradation of the surface of the part with presence of slightly scratched “whitened” areas.

No marks or scratches.

No lubricant residues.

Pick-up.

4. Conclusion

In our search for the most suitable sheet/tool contact configurations for warm forming of aluminum, a first selection was made from tribological tests. Press tests were then used to assess this selection under industrial conditions. The tribology results recommend the configurations with a coated and lubricated punch and exclude a use without lubricant, at the risk of immediate galling. In these tests, the lubricants had very close results while the coatings are better discriminated. The values of the coefficient of friction do not correlate with the observations of the pins and this could be explained by pin-lubricant interactions. A selection of 4 configurations was then made for the press tests. With the press tool, although the configurations with coating and lubrication bring good results especially with regard to the deposition of residues, those with bare punch and lubrication present the lower risk of galling. This last point differs from tribological results and is probably due to the difference in sheet-tool pressure between the two types of test. Finally, the “uncoated and lubricated tool” economical configurations proved to be better when compared to the “coated and lubricated tool” solutions and are of obvious industrial interest. As a further course of action, we plan to modify the tribological tests by decreasing the pressure of the pin and increasing the number of marks. We also plan to test other tool coatings that, hopefully, will show better levels of performance.

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