Analysis of Material Transfer From a Soft Workpiece to a Hard Tool: Part II—Experimental Verification of the Proposed Lump Growth Model

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In this study, the lump growth model, described in an accompanying paper (de Rooij and Schipper, 2000) is validated by means of experiments performed on a deepdrawing simulator. In the experiments, the influence of material and roughness properties of both sheet and tool on the galling behavior is determined. For these experiments, a deepdrawing simulator and a selection of aluminum and zinc coated sheets with several (coated) deepdrawing tools are used. Good agreement is found between results of the lump growth model and the sheet metal forming experiments. [DOI: 10.1115/1.1308023]

Introduction

Material transfer from the sheet to the tool, resulting in the buildup of lumps on the tool surface and consequently undesirable scratching of the product in sheet metal forming processes, is often called “galling”. If galling occurs, it will result in rejection of products because of poor surface quality. In a previous study [1], a theoretical lump growth model has been developed. In this model, the increase in size of a lump on the tool surface, by addition of material originating from the sheet surface, is modeled. The development of the summit height density of the tool surface caused by lump growth could be determined with the model. The model gave the possibility of determining the influence of several system properties (like tool roughness, height distribution, sheet hardness, load) on the growth behavior of lumps. Here, by means of experiments, the lump growth model is related to galling that arises under unlubricated deepdrawing conditions.

In the past, valuable research has already been done on the influence of tool and sheet properties on material transfer between contacting surfaces and galling. According to Clarck and Grant [2], material transfer depends mainly on tool roughness and lubricant performance. Schedin and Lethinen [3] propose a galling mechanism based on the ploughing effect of tool asperities through the sheet surface and the accumulation of transfer particles. Galling can be minimized by the use of a hard and a smooth tool surface, minimizing plastic deformation of the sheet through optimization of the microgeometry, and by increasing the hardness of the sheet surface. Avoidance of tool surface defects is important for galling reduction. According to Schedin and Lethinen [3], initiation of material pickup is difficult to avoid in practice and thus the growth of the transferred particles has to be controlled rather than the initiation. Galling can be minimized by transportation of wear fragments out of the contact zone using a suitable microgeometry of the sheet [4,5], or by increasing the resistance against subsurface plastic working. Roizard and von Stebut [6] have performed experiments to study metal transfer in metal forming processes. They find an increase in galling due to an increase in contact temperature and plastic bulk deformation of the sheet [7] and an influence of wear debris transportation out of the contact zone. Chen and Rigney [8] find that material transfer is

closely related to adhesion between the two surfaces. Then, surface energy gives an indication of the transfer tendency between metal surfaces. According to Clarck and Grant [2] pickup can be reduced or eliminated by proper “plateauing” of the tool surface.

According to Bernick et al. [9], nongalling and galling regions are found using a coordinate system relating two workpiece roughness parameters: PPI (peaks per inch) and $R_{\max}$. In [10] a critical contact pressure, above which galling occurs is found and an increasing resistance against galling with greater waviness of the steel sheet surface is reported. In the model presented in [1] galling is present if in the contact asperities operate in the wedge-formation regime, which is determined by the attack angle θ of the asperities and the dimensionless shear strength $f_{HK} = \tau/k$. Here, k is related to the hardness of the sheet and τ is the shear strength of the interface between tool and sheet. According to the lump growth model, lump growth can be decreased or restricted to less summits by a lower shear strength of the interface τ , a higher hardness of the sheet surface, and a lower roughness of the tool surface. It can also be decreased by a lower nominal contact pressure p , a higher hardness of the sheet H , and more wear debris removed from the contact zone. There is a transition (which is a function of tool roughness and other parameters), below which lumps will not be initiated and above which lump growth will occur.

Galling typically occurs in three stages: initiation of lumps on the tool surface, growth of the lumps, and a damaging stage where unacceptable scratching of the lumps occurs. It typically takes considerable sliding before lumps start developing and growing under realistic (lubricated) deepdrawing conditions. Because the initiation stage is not modeled with the lump growth model, experiments are performed under unlubricated conditions with rigorously cleaned surfaces to avoid the influence of the initiation stage on the experimental results as much as possible.

Experimental Setup

The experiments have been performed on a special purpose deepdrawing simulator called the RON tester, see [11]. The RON tester is a friction device that is built on a standard tensile tester. This tensile tester is used to clamp a strip of sheet material and to apply a tension force F_T to the strip (see Fig. 1). A drive is mounted on the tensile tester and is used to move the friction device along the strip, if desired simultaneously with plastic deformation of the strip.

The sheet materials, used in the experiments, are regularly used in industrial deepdrawing. Most experiments have been performed

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Fig. 1 The RON tester is mounted on a tensile tester

Table 1 Material properties of the sheets used in the experiments

Code	RMS roughness σ_z [μm]	thickness d [mm]	elastic modulus E [GPa]	yield stress σ_y [MPa]
1050A W7	0.32	1	70	85
6016 T4	0.36	1.13	70	143
6016 T4	1.29	1.15	70	121
TSULC GA	2.6	0.7	210	170
zinc layer		7 μm	pm. 90	Hardness, see Fig.
TSULC GI	1.28	0.7	210	185
zinc layer		μm	pm. 90	145

with AA 1050A W7, AA 6016 T4 MF, and AA 6016 T4 aluminum sheet. The main difference between AA 1050A W7 and 6016 T4 MF is the hardness. The hardness of the former is lower than the hardness of the latter. The difference between 6016 T4 MF and 6016 T4 EDT is the roughness. The mill-finish (MF) material has a strongly anisotropic roughness, while the electrical discharge texturing material has a much more isotropic roughness, see [12]. Besides this, experiments using two types of zinc-coated sheet material, Galvannealed (GA) and galvanized (GI), will be discussed. Some sheet material properties are summarized in Table 1.

In the experiments, cylindrical tools with a radius of 10 mm were used. Such tools result in line contacts between the sheet and the tool. If not mentioned otherwise, experiments are performed using DLC coated tools.

Experimental Results

It is of great importance to have an objective measure for the severity of galling. From experiments, it turns out that the standard deviation of the coefficient of friction σ_f is a more sensitive indicator for the amount of transferred material rather than the average coefficient of friction f itself. A disadvantage of this friction-based galling criterion is that it is indirect. A high standard deviation of the coefficient of friction σ_f could be caused by effects other than material transfer, like the presence of scratches in the sheet or stick-slip effects. Using this indirect criterion together with direct, but subjective visual inspection of the tool surface, gives a practical and sensitive galling indicator. Therefore, besides σ_f , a measure G , ranging from 0 to 5, is used to indicate galling. $G=0$ means no material transfer (as observed with the naked eye) and $G=5$ means extensive material transfer.

Table 2 Results with DLC coatings

coating	σ_z [μm]	f [-]	σ_f	G
DLC	0.286	0.21	$8.5 \cdot 10^{-3}$	1
DLC	0.164	0.16	$7.1 \cdot 10^{-3}$	1

If galling is indicated by σ_f and G , these values were obtained after the standard sliding distance of 0.5 m. The average coefficient of friction f and the standard deviation σ_f were measured over the whole friction signal, with the exception of a possible running-in phase. As far as possible, experiments with the same coating material and tool roughness have been performed on different parts of the same cylindrical tool. This was done to avoid influence of slight roughness differences between different cylinders.

Aluminum Sheet Material

Tool Roughness. Generally, the tool, coated with the standard (DLC) coating, showed almost no wear and not much material transfer. In many cases, the surface of the coating had a polished appearance after performing the experiment. This means that high-frequency roughness details are worn off from the highest spots of the coating surface. Table 2 shows the results for a smooth and a rougher DLC coated tool.

In these experiments, a sliding velocity $v=0.005$ m/s, sliding distance $l=0.5$ m, and an applied normal force of $F_N=350$ N were used as operational conditions. These conditions in the following will be referred to as the “reference” experimental conditions. The reference aluminum sheet material is AA 6016T4 MF. The strip is clamped into the tensile tester under low elastic tension, i.e., $F_T \approx 600$ N. The combined effect of this tension force and applied normal force results in a average normal contact pressure of $p \approx 120$ MPa, according to elastic-plastic FEM calculations [13].

Experiments to study tool roughness effects on galling have been performed with a standard DLC coating under reference conditions. The coating is deposited on cylindrical tools that have been ground and, eventually, polished to determine the influence of roughness of the tool on galling. Summit height densities of DLC coatings on a ground substrate had a Gaussian appearance. The summit height densities of DLC coatings on a polished tool had a negatively skewed appearance, see Fig. 2.

Experimental results, represented by σ_f and G , are shown in Fig. 3. It should be noted that the x scale is not linear. It is clear that a lower surface roughness reduces material transfer. The transition from little material transfer to much material transfer occurs within a fairly narrow range of σ_z values. Polishing of the substrate before deposition of the coating (the two smoothest cases) reduces material transfer. This is in agreement with the results of the model, which states that a lower roughness as well as a surface characterized by a negatively skewed summit height distribution, obtained by polishing [1] or plateauing [2] of the tool, will reduce material transfer.

Even in the case of transfer resistant surfaces like a DLC coating, deposited on a highly polished substrate, very small lumps of transferred material (size smaller than 1 μm) were clearly visible after short sliding distances (because of the high contrast between the deep-black DLC coating and the metallic aluminum) by optical microscopy. However, these lumps were not large enough to cause damage to the sheet and can therefore not be considered as galling, i.e., undesirable and potentially causing damage to the sheet. However, this indicates that lumps initiate easily under unlubricated circumstances. These lumps might finally cause damage to the sheet, when given sufficient possibilities to grow, i.e., after long sliding distances. The initiation of these small lumps can be explained as follows.

Roughness is a phenomenon occurring at many length scales. In fact, measured surface slopes increase when the measurement

Fig. 2 Summit height densities, obtained from measured height data of the (unused) tools, using a nine-point summit criterion. The ground surfaces have a Gaussian appearance and the polished surface have a negatively skewed appearance

bandwidth is widened to include finer roughness details [14]. This means that at realistic rough surfaces there will always be a roughness scale at which slopes are high enough for the summits to reach into the wedge-formation regime, if $f_{HK} > \approx 0.5$. Defects in the tool surface correspond to locally high attack angles and will easily form initiation sites for lumps, see [3]. It can be concluded that roughness characteristics of the tool are dominant factors regarding material transfer.

In Fig. 4 the relation between galling and the applied load is shown. The σ_f and G values, shown in Fig. 4, indicate that there is indeed an influence of the load on material transfer for the standard DLC coating sliding against AA 1050 MF at approximately 400 N. This can be explained by a transition from the ploughing regime to the wedge-formation regime for some critical asperities on the tool surface. This is in agreement with the galling model, because the attack angle θ of the uppermost asperities on the tool into the sheet surface increases with increasing load. In the model, this results in a transition load, above which galling occurs. This was also found in [10].

Figures 5 and 6 show the values of G and σ_f using the standard DLC coating on tools for the three aluminum sheet materials.

Fig. 3 The severity of galling, indicated by G and σ_f , as a function of rms tool roughness for DLC coatings (sliding against the reference sheet material AA 6016T4 MF under reference experimental conditions). The x axis is not a linear scale, but represents different coated samples.

Fig. 4 The severity of galling, indicated by G and σ_f , as a function of applied normal force F_N for DLC coatings sliding against AA 1050 MF material under “almost” reference experimental conditions, except that $v=0.005$ m/s

AA 6016T4 MF and AA 1050W7 MF mainly differ in hardness. It is clear that in most cases and, in particular, at a higher roughness of the tool, AA 1050W7 MF (the softer sheet) resulted in more material transfer than AA 6016T4 MF (the harder sheet). This trend is in agreement with the model, where a lower surface hardness of the sheet increases lump growth; see also [3].

Fig. 5 The severity of galling, represented by G , as a function of tool roughness for different kinds of aluminum sheet material

Fig. 6 The severity of galling, represented by σ_f , as a function of tool roughness for different kinds of aluminum sheet material

Table 3 Results with zinc coated sheet material

	uncoated	TiCN	DLC1	DLC2
GA	0.18	0.20	0.085	0.08
GI	0.14	0.14	0.115	0.11

Zinc Coated Sheets. It is known from industrial practice that, as is the case with aluminum sheets, the usage of zinc coated sheets often result in material transfer to the tool. Because zinc coated material is now more commonly used in industry than aluminum sheet material, some experiments have been performed with two zinc-coated materials, i.e., GA and GI material. Some experiments have been done earlier by ter Haar [11] using these materials under lubricated conditions on the same tester.

The frictional behavior, found when using uncoated tools under unlubricated conditions, is very much the same as the frictional behavior measured by ter Haar [11] under lubricated conditions, using a mineral oil without additives. The measured coefficients of friction correspond well with these results. In both cases, transfer of the zinc layer to the tool surface was found. In both cases the use of GA material often resulted in stick-slip effects, although in the present work stick-slip resulted in higher average coefficients of friction than in [11], i.e., $f=0.18$ against $f=0.14$. It can be concluded that a pure mineral oil (used by ter Haar) is not so functional in the case of zinc coated sheet materials. The frictional behavior is apparently determined by a transfer film, which is formed on the tool, and not by a protective boundary layer, formed by the lubricant. Plastic predeformation with a logarithmic strain of 15 percent did not influence the frictional behavior significantly. The low coefficients of friction and the low influence of plastic strain on friction are in agreement with literature [15]. Deposition of a TiCN coating did not make much difference compared to the uncoated tool in the measured coefficients of friction as can be seen in Table 3.

The appearance of the transfer film on the tool was different from that found with aluminum sheets. In the case of aluminum sheets buildup of high separate lumps was found. This was much less the case when using zinc coated materials. Especially in the case of GA material a continuous transfer film was found (see Fig. 7) that shows the TiCN coated tool surface after sliding against GA and GI material. In this case, the sheets have been predeformed to a logarithmic strain of the sheet of 15 percent. The difference in transfer behavior can be explained by differences in the structures of, respectively, the GA layer and the GI layer.

For the GA material diffusion of Fe from the underlying substrate results in a harder coating with a layered structure, see Fig. 8. The uppermost layer is a very soft η phase (pure Zn). The low hardness of this uppermost layer explains the relatively high amount of transferred material in the case of GA material. However, the soft Zn layer is very thin (typically thinner than $0.3 \mu\text{m}$).

In terms of the lump growth model, transfer in the form of a continuous transfer layer instead of in the form of separate lumps means that material is not predominantly deposited on top of the

Fig. 7 Material transfer of GA and GI material to the TiCN coating

Fig. 8 The schematic structure of the galveanneal layer GA and the galvanize layer GI, together with SEM photographs of color etchings of the GA and GI layer

highest tool summits. The model showed that, typically, the height increase Δs is higher for higher summit heights s . In the case of GA however, the highest summits will penetrate the η phase and thus make contact with the harder ζ phase while the lower summits contact the softer η phase. This means that the height increase may well be more pronounced in the case of the lower summits than in the case of the higher summits, i.e., $\Delta s_{\text{low}} > \Delta s_{\text{high}}$. Eventually, the lower tool summits will catch up in height with the higher tool summits. This would explain the formation of a continuous transfer layer instead of distinctive lumps.

GI material, contrary to GA material, has a more uniform hardness over its thickness (see Fig. 8). Perhaps the ‘hardness gradient’ in the sheet surface is one of the factors that determine whether transfer takes place in the form of separate lumps or in the form of a continuous film. Transfer in the form of a continuous film reduces the risk of damaging the surface by scratching and would therefore be favorable.

Deposition of a DLC coating on the tool resulted in low coefficients of friction, i.e., around $f=0.09$ for GA material and around $f=0.11$ for GI material. Transfer of zinc was not found, either for the smooth DLC (DLC 2, $\sigma_z=0.035 \mu\text{m}$) or for the rougher DLC (DLC 1, $\sigma_z=0.286 \mu\text{m}$), not even when viewed at $100\times$ magnification with an optical microscope. Besides this, the roughness of the DLC coating did not significantly influence the measured coefficient of friction (see Table 3). This result is different from the experiments using aluminum sheet discussed above, where very small lumps were found on the tool surface under the same conditions and a higher coefficient of friction was measured.

According to the model, transfer can never occur below $f_{HK} = \tau/k \approx 0.5$ (τ is the shear strength of the interface, and k is the shear strength of the softer contact partner), because then no summits operate in the wedge-formation regime [1]. When the ploughing component is neglected, this would correspond to a coefficient of friction of $f \approx 0.1$, see [13]. This explains the absence of material transfer when using zinc coated sheets, despite the relatively high roughness of the tool and the very low (surface) hardness of the sheet.

Conclusions

- Although the roughness of the tool is almost negligible compared to the roughness of the sheet, it is of great importance with respect to galling.

- According to the experiments, galling can be minimized by a low tool roughness, an appropriate coating material (e.g., DLC), and a high (surface) hardness of the sheet.
- Polishing of the (PVD coated) tool, resulting in a lower roughness of the tool, reduces galling.
- Material transfer is difficult to prevent under totally unlubricated conditions. It will, even under favorable operational conditions, often occur on a microscale. This results in small lumps on the tool surface. In time, these lumps may grow and damage the sheet.
- The roughness of the sheet has little influence on the galling behavior.
- The trends, derived from the experimental results, are in general agreement with trends from the calculations with the lump growth model. This gives confidence in the assumed galling mechanism, i.e., a wedge-formation mechanism.
- The lump growth model does not include a limiting size for the lumps. It is obvious that in reality such a limiting size exists. The model should be expanded to take the limiting size of lumps into account.

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