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Frictional Behavior of the Sliding Interface between an A2 Steel Die and Zinc-Coated Steel Sheet

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The forming of coated sheet steel products is performed for a wide range of processing conditions. This article examines the effects of die history on the frictional nature of the sheet-die interface. It has been found that as successive tests are performed on a die from the as-lapped condition to the "run-in" condition, the die surface morphology changes significantly and the coefficient of friction, μ, decreases. Changes in surface roughness as well as scratch formation on the die are believed to affect the nature of the die-workpiece, lubricant interaction. The findings in this study suggest that the extensive polishing procedures used in the manufacture of new stamping dies should be carefully reevaluated.

Keywords stamping, stamping dies, tribology, zinc-coated steel sheet

1. Introduction

Friction phenomena are often classified according to the lubrication conditions present as thick/thin film, boundary, or mixed regime lubrication (Ref 1).

The thick film lubrication condition occurs when steady flow is achieved between surfaces at high pressure and subsequently high Reynolds numbers. This condition is rarely seen during normal metal forming operations. The thin film lubrication condition is very similar to thick film lubrication except that there is less lubricant separating the two surfaces.

In the second condition, boundary lubrication, there is no layer of lubrication separating the two sliding surfaces. This condition, which has relatively high sliding friction when no lubricant is present, is also rarely seen in metal stamping and drawing operations.

The final condition, mixed lubrication, is a combination of thin film and boundary lubrication. The fluid lubricant is able to bear enough pressure to keep some areas of the sliding surfaces from having intimate contact. Some areas, however, due to either high pressure or surface geometry, break through the lubrication barrier, and there is intimate contact between the sliding surfaces. This condition is most often present during stamping operations.

The testing completed for the present study was performed in the mixed lubrication regime. In order to understand the nature of friction phenomena in the mixed regime, both thin film lubrication and boundary lubrication must be considered.

Theories regarding nature of the frictional resistance mechanism have been evolving since the time of Leonardo da Vinci. Originally frictional resistance was thought to be a result of ratchetting surface features or the geometric interference of two rigid sets of asperities (Ref 1). As more advanced frictional theories and experiments developed, other parameters describing the nature of the sliding materials and the sliding system were recognized, and attempts have been made to quantify these effects. Among the many different parameters are mechanical properties of the interface materials (e.g., hardness, surface morphology, flow strength), chemical properties (e.g., bonding affinity, surface oxidation, lubricant interaction), and system conditions (e.g., interface speed, pressure, geometry) (Ref 2, 3).

The effects of die history on the frictional characteristics of the tool-workpiece interface are dependent on all of the previously listed parameters; however, some of these parameters have second order and higher relationships to friction, while other parameters have more direct effects. The most important parameters for this study were surface morphology, lubrication, and mechanical properties of the surfaces.

The morphology of the surfaces will in large part determine the amount and shape of the areas of intimate contact at the interface, the amount of lubricant wetting, and the nature of the surface deformation during sliding. The lubricant applied to the sliding interface can affect friction by either bearing part of the normal load, and thus preventing intimate contact, or by chemically inhibiting adhesion bonding of the two surfaces. The ability of the lubricant to protect the die surface in either of these two manners will be reflected in the frictional character of the die. Likewise, the mechanical properties, specifically hardness, will determine how parts will wear with repetitive tests. Generally, a harder part will be less susceptible to surface morphology changes during sliding contact.

The objective of this article is to examine the changes that occur with time in the coefficient of friction during the sliding of zinc coated sheet steel against a tool steel die. The causes for the changing friction coefficient are also explored in this article.

2. Friction Test Apparatus

Bending under tension (Ref 4, 5) and draw bead simulator (Ref 6, 7) type friction testers have been extensively used for frictional characterization of sheet steels during stamping operations. The draw bead simulator and bending under tension

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type tests impart plastic bending and tensile strains to the bulk material of the workpiece during testing. This bulk plastic deformation of the workpiece changes the surface morphology. The observed changes in surface morphology will therefore be due to both the workpiece sliding over the die as well as the bending and unbending processes.

A flat die type tester imparts less complex loading on the bulk of the sheet and thus also on the surface of the sheet during testing. The bulk material is in an elastic stress state during the test; therefore, any plastic deformation of the surface occurs only as a result of the workpiece sliding against the dies.

The surface morphology of sheet steels is thought to affect the frictional characteristics of the sheet during forming (Ref 8-11). In order to examine the morphology that results from tool on workpiece sliding, a flat-die type friction tester was designed and built. While the coefficient of friction is recorded for tests performed on this machine, the primary use for this machine is to create a controllable surface deformation of test specimens. This controlled deformation can be used to observe the development and changes in the steel sheet surface morphology during sliding against the tool without the confounding effect of bending.

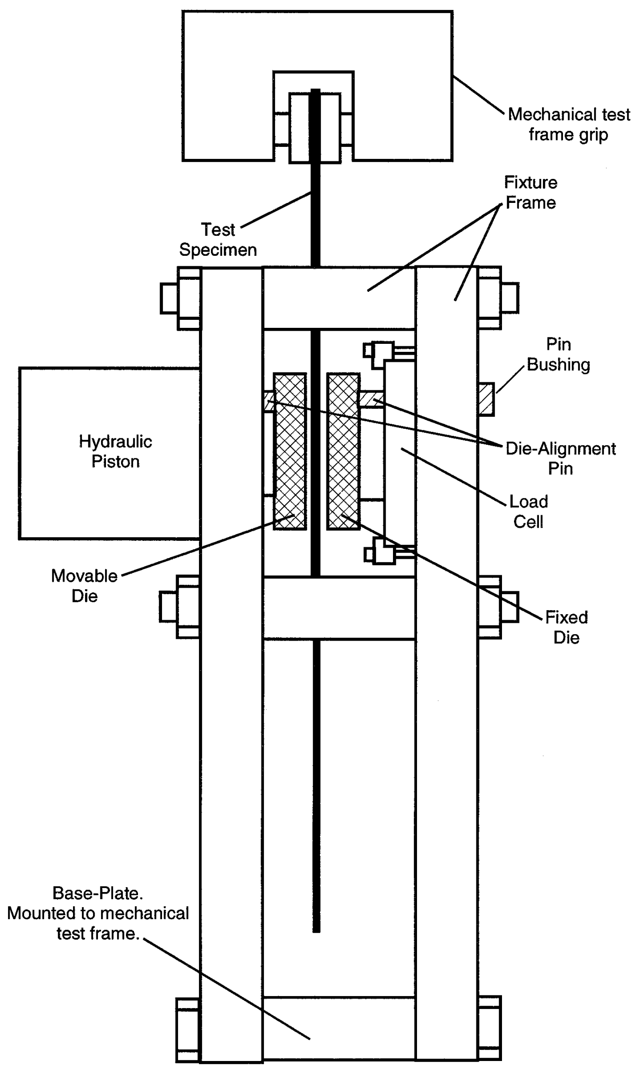


Fig. 1 Schematic diagram of clamping system on flat-die type friction test apparatus

Figure 1 shows a schematic diagram of the clamping system for the friction tester. The test specimen, a 50.8 by 406 mm zinc coated sheet steel strip, was clamped between two A2 tool steel dies; one die was movable in order to apply the load, and the other die was rigidly attached to a load cell. The dies were both hardened to 60+ HRC and polished to a surface finish of 0.2 μm. The bottom edge of each of the dies was ground to a 2.0 mm radius to avoid scoring of the test specimen and facilitate lubricant penetration between the dies and the workpiece.

Clamping force was provided by an 88.5 kN hydraulic piston, which was attached in series to a nitrogen charged accumulator to maintain constant clamping force during each test. The charge in the accumulator also regulated the maximum pressure at which the hydraulic system could operate. The clamping force was measured by a load cell, which was located behind the stationary die. Between the hydraulic piston and the movable die was a self-centering washer, which corrected for any minor misalignment between the movable die and stationary die, thus avoiding problems with "rocking" of the movable die during testing. Both dies were equipped with alignment pins to eliminate movement during testing and ensure consistent die positioning.

The clamping system (dies, hydraulic piston, and load cell) were mounted on two 25.4 mm thick steel plates called back plates. The spacing between these plates was maintained by four 25.4 mm diameter rods and a 25.4 mm thick steel plate. The back plates were held together by two 8.85 kN U-clamps. The U-clamps were used so the dies could be removed from the test apparatus and the surfaces checked at regular intervals.

The pulling force was provided by the actuator from a commercial mechanical test frame to which the friction tester was attached. The actuating piston was used to apply a fixed rate displacement to the test specimen. The pulling force required to achieve the desired displacement rate was measured by a load cell in series with the actuator and the test specimen.

The dies of the flat die type friction tester were in contact with both sides of the coated sheet steel test specimen during testing. This condition required that when calculating a coefficient of friction, μ, the sliding resistance from both sides must be taken into account. The equation used for calculating μ is:

$$\mu = F_{\text{pulling}}/2 \cdot F_{\text{clamping}} \tag{Eq 1}$$

where F_{pulling} is the pulling force from the actuator and F_{clamping} is the clamping force from the dies.

3. Test Procedure

The coated sheet steel tested for the current study was a commercially produced low carbon sheet steel with an electrogalvanized coating, designated EG. Tables 1 to 4 give substrate chemistry, mechanical properties, coating weight, and coating chemistries. The steel was sheared into rectangular specimens 50.8 by 406 mm, and the edges were deburred to ensure even contact with the die surface.

The lubricant used for the current tests was a prelube mill oil produced by Henkel Corporation (Germany) designated as lubricant 1. Infrared spectrum analysis and ASTM D 445-94 tests were performed on the lubricant to determine chemical makeup and viscosity. The lubricant was an aliphatic hydrocarbon, with some addition of esters. The kinematic viscosity was fairly high at 200.5 cSt.

The flat-die type friction tester had two setup parameters: clamping pressure and interface sliding velocity. The maximum clamping force was adjusted using a nitrogen filled fluid accumulator. For the current study a single clamping force, 4.4 kN, was used for all tests. Interface sliding velocity was controlled via the actuator on the mechanical test frame to which the friction tester was attached. A single interface velocity, 4.23 mm/s, was used for all tests.

4. Test Results: Die Surface Effects

The effect of die wear on the coefficient of friction, μ, can be seen in Fig. 2, which shows μ plotted as a function of test sequence. Three die sets are identified in the figure. Descriptions of the different die conditions are:

- Die set 1 was used for approximately 200 test runs before the tests shown in Fig. 2 were performed. Die set 1 was thus considered to be in the "run-in" condition.
- Die set 2 was polished to 0.2 μm before testing began. Three materials were tested on this die set: the EG material, which is the focus of the current article; a galvannealed sheet steel; and an uncoated sheet steel.
- Die set 3 was ground with 600 grit paper parallel to the direction of testing before testing was performed to create a surface finish similar to that of the run-in dies.

The μ-values obtained with die set 1 show some scatter, but are clustered around μ = 0.11. Die set 2, however, shows a significant change in coefficient of friction values with an increase in the number of test runs performed. Approximately 150 tests, including tests of other material-lubricant combinations, were performed on die set 2. The coefficient of friction for the EG material with lubricant 1 decreased from about 0.16 at the beginning of testing to less than 0.12 after over 150 tests. The μ values obtained for die set 3 in Fig. 2 show some scatter, but are again clustered around μ = 0.12.

The only observable change in the test apparatus, during the testing performed with die set 2, was the die surface condition. Figure 3(a) shows a photomicrograph of the die surface as polished with no testing performed. On the relatively smooth unscratched surface the only noticeable features are spherical second phase particles (most likely carbides) with an average diameter of about 1.0 μm. In Fig. 3(b) the die surface after more than 150 tests is no longer smooth. Scratches, approximately 1.0 μm deep by 1.0 μm wide, in the test direction are present. These scratches can result from the pulling out and subsequent sliding of spherical carbides along the interface.

Die surfaces in the as-polished and well run-in conditions were examined using an optical interferometry type three-dimensional surface profiler. Two significant observations about

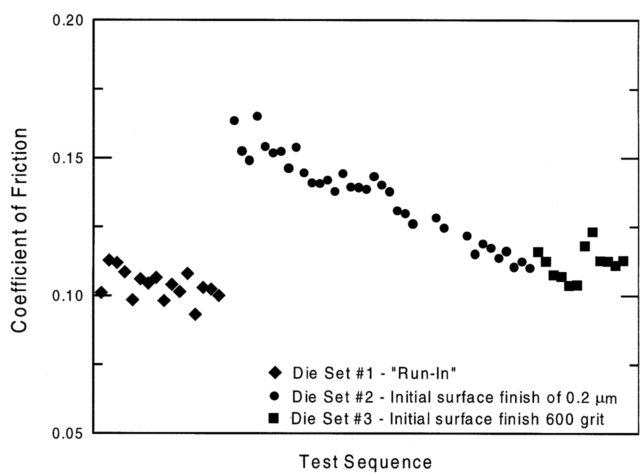


Fig. 2 Effect of test sequence on μ for EG6 material lubricated with lubricant 1. Three data sets are shown: a run-in die set, a die set with an initial surface finish of R_a = 0.2 μm, and a die set with an initial surface as ground with 600 grit paper.

Table 1 Base steel chemistry (in wt%)

Material	C	Mn	S	P	Si	Cr	Al	Ti	Cu	N
EG	0.015	0.21	0.008	0.01	0.013	0.19	0.035	0.003	0.013	0.007

Table 2 Base steel mechanical properties

Material	Yield strength, MPa	Tensile strength, MPa	Uniform elongation, %	r bar, normal anisotropy	*n*, strain hardening exponent
EG	165	291	23	1.6	0.22

Table 3 Zinc coating weight

Material	Top coating weight, g/m^2	Bottom coating weight, g/m^2
EG	60	60

Table 4 Zinc coating chemistry (in wt%)

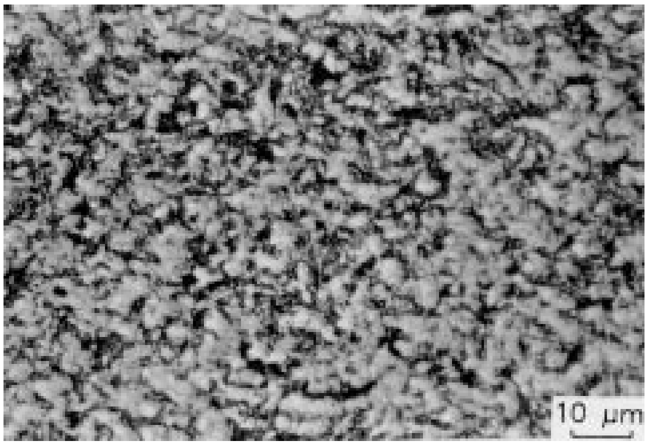
Material	Fe	Ni	Al	Sb	Pb
EG	0.12	0.001	<0.0001	0.001	0.001

the die surfaces were made using this equipment. First, the overall average roughness, R_a, value of the run-in dies was lower than that of the as-polished dies, 135 nm compared to 155 nm. Second, the areas directly adjacent to the scratches showed some upheaval and a correspondingly higher R_a, 203 nm. Figure 4 illustrates a three-dimensional profile of a scratched region showing the upheaval.

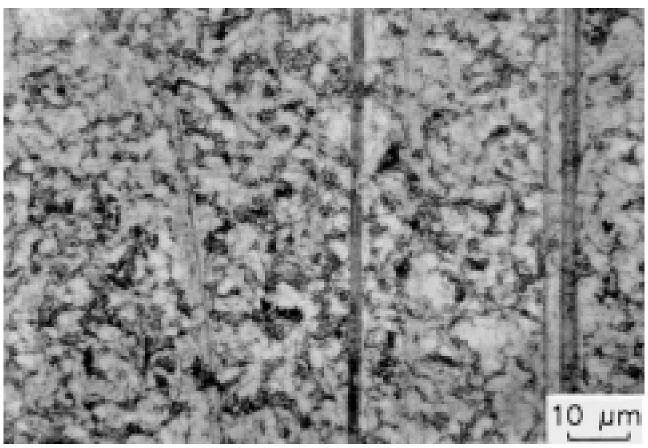
Zinc buildup on the die surface was tested by applying a $CuSO_4$ solution, which turns black upon contact with zinc. No zinc buildup was detectable using this technique. However, the zinc coating did powder, leaving a fine dispersion of zinc in the lubricant remaining on test specimens after testing.

An additional set of tests was performed to confirm the results showing the decrease in μ with successive testing. Whereas the previous observations were made during testing of several material-lubricant combinations on a single die set, another set of test results was compiled using one material-lubricant combination on a dedicated die set. A die set was polished to a surface finish of 0.2 μm, and a series of tests using only the EG material with lubricant 1 was performed. Figure 5 shows the results for this set of tests. The results again show that there is a steady downward trend in the μ-values as the number of tests performed increases.

The decrease in μ in Fig. 5 is not as sharp as it was for die set 2 in Fig. 2 because the results from die set 2 were accumulated from a die set subjected to over 150 tests, whereas the dies in Fig. 5 were subjected to approximately 50 tests and were thus still in the "running-in" stages. Die set 2 in Fig. 2, which shows about three times as large a change in μ, also was subjected to three times as many tests. The additional testing confirmed that the decrease in μ was due to the number of tests performed on the die set and not an artifact of the other material-lubricant systems tested on die set 2.



(a)



(b)

Fig. 3 (a) Die surface as polished to a nominal R_a of 0.2 μm die set prior to testing. (b) Die surface shown in Fig. 2 after 100+ tests. Scratches with a width of 1.0 μm can be seen running in the direction in which sheet specimens were tested.

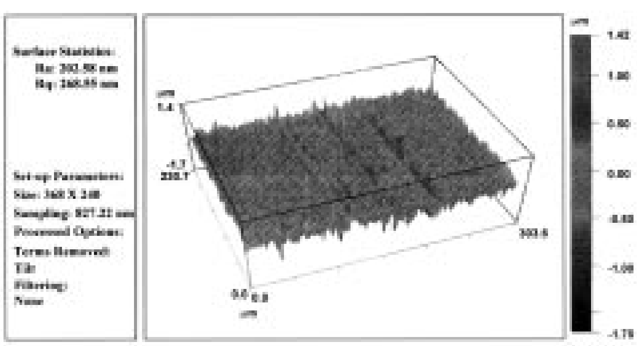


Fig. 4 Three-dimensional surface profile of tested die surface in scratched region

5. Discussion: Die Surface Effects

During the friction testing performed for this work, the surfaces of the tool and the workpiece both played a role in determining the frictional nature of the system. The die surface morphology changes during the testing program; more scratches and upheavals are formed while simultaneously the bulk surface of the die is being smoothed. The individual

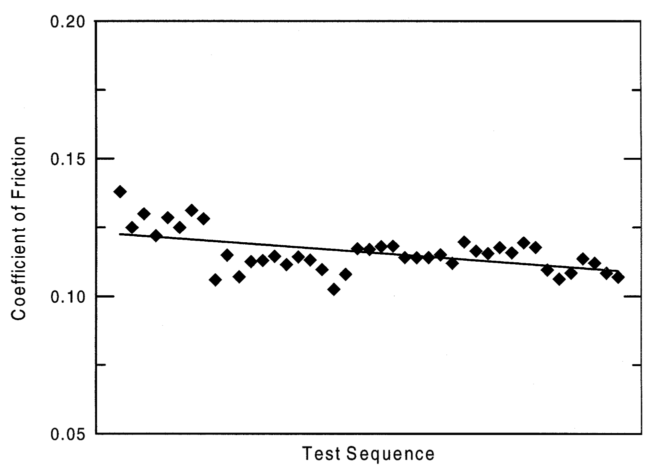


Fig. 5 Additional testing performed on a dedicated die set to confirm the decrease in μ as a function of number of tests performed on a given die set

coated sheet steel test specimens, however, all have essentially identical surface features at the beginning of each test. All other test parameters were also held constant throughout testing. The decreasing friction coefficient with an increasing number of tests performed was, therefore, a result of only the die surface morphology changes.

Changes to the die surface during the testing can be divided into three separate categories: (a) development of scratches, (b) local upheaval and roughening in areas adjacent to scratches, and (c) overall decrease in average roughness (i.e., smoothing).

The effect on friction from each of these three categories can be described in the following manner. The scratches that were observed on the die surface had two different morphologies. All scratches ran parallel to the sliding direction; however, the scratches differed in starting and ending locations. Some scratches ran the full length of the die. These were termed "nonterminating" scratches. Other scratches that started or stopped before reaching a free edge of the die were termed "terminating" scratches. The effect of these two scratch morphologies on the frictional resistance at the interface can be explained in terms of changes in the lubrication condition. The nonterminating scratch acts as a channel for pressurized lubricant at the interface to flow to a free edge of the die. This point is discussed by Dalton and Schey (Ref 12) in their treatment of die surface effects on interface friction. As the lubricant flows out of the interface it no longer bears as much of the normal load at the interface, and thus no longer acts to separate the die and workpiece surfaces. Such an effect would allow a greater amount of intimate contact between the sliding surfaces. Greater intimate contact and less lubricant load bearing in isolated pockets leads to more solid state bonding and thus greater frictional resistance at the interface.

Scratches that terminate before reaching a free edge of the die would conversely trap lubricant. This effect would be similar to the transverse scratches discussed by Dalton and Schey (Ref 12). As pressure at the interface and in the lubricant increases, the lubricant is forced out of the scratches and into the interface. This action would effectively decrease the amount of intimate contact between workpiece and die and also increase the amount of lubricant load bearing, thus lowering the frictional resistance.

The second major change in the die surface morphology occurred in regions adjacent to scratches where material upheaval was observed. Figure 4 shows a three-dimensional surface profile of a series of three scratches and their adjacent regions of upheaval. These upheavals can potentially affect friction by two different modes. The first effect would be decreasing the intimate contact area and increasing the lubricant entrapment volume. The height of the upheavals, 1.4 μm, is comparable to the average roughness of the EG material, $R_a = 1.4$ μm. In areas where upheavals are present the sheet will be lifted away from the die surface by the upheavals, causing a small gap at the interface where lubricant will be able to enter areas of previous intimate contact. This decrease in intimate contact area and increased potential for lubricant penetration would lead to a lower frictional resistance.

The upheavals also provide a potential increase in the geometric interference, that of the harder upheavals plowing through the softer coated sheet steel. This increased interference between the workpiece and the die during sliding would result in greater frictional resistance. Continuous scratches on tested coated sheet steel specimens, indicative of hard surface features on the die plowing through the softer coating on the steel surface, were regularly observed.

The third major change in the die surface noted during testing was an overall decrease in the average roughness. This smoothing of the die surface can have two opposing effects. A smoother surface offers more intimate contact and thus less lubricant entrapment with more area for adhesion to occur. The result would be an increase in frictional sliding resistance. Conversely, an increase in true bearing area under the same normal load would cause a decrease in local pressure on the surface. This decrease in local pressure would decrease the amount of solid state bonding, which in turn would result in a less frictional sliding resistance at the interface. A smoother surface also provides less geometric interference than rougher surfaces also leading to less frictional sliding resistance than an otherwise similar rough surface.

The average roughness values for the A2 tool steel die and EG sheet steel workpiece were respectively 0.2 and 1.4 μm, an order of magnitude different. The change in the R_a value of the die surface was on the order of 0.02 μm, which is approximately a 10% change with respect to the original die surface or approximately a 1% change with respect to the roughness of the coated sheet steel. The frictional effects from the overall smoothing of the die surface may have been so small that they were insignificant with respect to the decreasing μ observed during testing. With the surface of the sheet having a much higher R_a and also being softer, the amount of lubricant entrapment and contact area development would be a stronger function of the workpiece than of the die in the absence of scratches.

Assuming that the smoothing of the die surface is an insignificant effect relative to the development of scratches and upheavals on the die surface simplifies the explanation of the observed decreasing μ with increasing number of tests performed. Scratch and upheaval development both have the potential either to increase or to decrease the frictional resistance at the interface. Considering only scratches, a greater percentage of nonterminating scratches would increase the frictional resistance; whereas, a greater percentage of terminating scratches would decrease the frictional resistance. The effect from upheavals is dependent upon which mechanism has a greater effect, the increase in lubricant penetration coupled with a decrease in true contact area or the geometric interference, that is, plowing of the coated sheet steel surface by the upheavals.

Because a decreasing μ was observed with an increasing number of scratches and upheavals, it appeared that the combined effects of increased lubricant penetration and decreased true area of contact from both terminating scratches and upheavals had a greater contribution than geometric interference from upheavals and decreased lubrication from nonterminating scratches. Thus the net decrease in the ability of the interfaces to form solid state bonds appeared to be the controlling factor in the observed decrease in μ with increasing the number of tests performed.

6. Conclusions

The following conclusions can be drawn:

- Decreasing coefficient of friction values were observed with increasing number of tests performed on a single die set.
- Decreasing coefficient of friction depends on changes of the die surface morphology during testing.
- There were three potential mechanisms for change in μ observed during testing: scratch development on die surface, upheaval development on die surface, and overall smoothing of the die surface.
- Increasing numbers of nonterminating scratches and upheavals lead to increased lubricant penetration and decreased true area of contact, which under constant normal-load friction testing result in a decrease in the coefficient of friction.

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References

1. K.C. Ludema, Friction, *Wear Lubrication: A Textbook in Tribology,* CRC Press, New York, 1996
2. F.P. Bowden and D. Tabor, *The Friction and Lubrication of Solids,* Parts I and II, Oxford University Press, 1964
3. H. Czichos, Basic Tribological Parameters, *Metals Handbook,* Vol 18, *Friction, Lubrication, and Wear,* ASM International, 1992, p 473-479
4. D.W. Vallance and D.K. Matlock, Applications of the Bending-Under-Tension Friction Test to Coated Sheet Steels, *J. Mater. Eng. Perform.,* Vol 1, 1992, p 685-693
5. T.A. Hylton, "Frictional Behavior of Electrogalvanized Sheet Steels," Ph.D. thesis, T-4521, Colorado School of Mines, Golden, CO, 1994
6. H.D. Nine, Draw Bead Forces in Sheet Metal Forming, *Mechanics of Sheet Metal Forming,* D.P Koistein and N.M. Wang, Ed., Plenum Press, 1978, p 179-211
7. J.A. Schey, "Solid-Film Lubrication of Galvanized Sheets," SAE Technical Paper No. 950697, 1995
8. N. Bay and T. Wanheim, Real Area of Contact and Friction Stress at High Pressure Sliding Contact, *Wear,* Vol 38, 1976, p 201-209
9. J. M. Challen and P.L.B. Oxley, A Slip Line Field Analysis of the Transition from Local Asperity Contact to Full Contact in Metallic Sliding Friction, *Wear,* Vol 100, 1984, p 171-183
10. K. Miura, T. Hira, O. Furukimi, and T. Obara, Zinc Coated Steel Sheets with Superior Press Formability and Image Clarity, *Proceedings of the 37th Mechanical Working and Steel Processing Conference,* Vol 33, Iron and Steel Society/AIME, 1996, p 173-178
11. T. Mizuno and K. Hasegawa, Effects of Die Surface Roughness on Lubrication Conditions in the Sheet Metal Compression-Friction Test, *J. Lubr. Technol. (Trans. ASME),* Vol 104, 1982, p 3-11
12. G.M. Dalton and J.A. Schey, "Effect of Bead Finish on Friction and Galling in the Drawbead Test," SAE Technical Paper No. 920632, 1992