

Determination of Frictional Behavior in Sheet Metals Using Orthogonal Arrays

D.P. Kotchman, I. Kim, C.-Y. Sa, and D. Lee

Frictional behavior of two sheet materials, aluminum-killed drawing-quality steel (AKDQ) and electrogalvanized (zinc) drawing-quality steel (AKDQ-EG), is examined under conditions of varying die material, die radius, crosshead speed, and lubricant. Tests are conducted using a special apparatus designed to measure front and back tension on uniform tensile strip specimens pulling over a circular die, simulating both frictionless and frictional conditions under certain sheet-metal-forming conditions. Use of a specially designed test apparatus with four contact angles for the same test condition minimizes the error associated with the use of single measurements for the determination of friction coefficient. Lubricant and die material play important roles among different factors examined in determining the coefficient of friction. Die radius has the most pronounced effect on the coefficient of friction. Implication of these results on actual sheet forming processes are discussed.

1. Introduction

FRICTION associated with manufacturing processes play an important role in defining process limitations. It has a critical role in defining materials, lubricants, die geometry, and machine parameters necessary to successfully produce a part.[1] In the automobile and appliance industries, the manufacture of sheet metal components such as automobile body panels and refrigerator casings is greatly influenced by frictional considerations. For example, deep drawing plastically deforms the metal sheet blank, using a punch to push the blank into a die. Friction alters stress and strain distributions during such deformation. Friction is known to be influenced by even slight variations in lubricating conditions, in homogeneous deformation, die surface characteristics, and stress distributions across the area of contact between the blank and die or punch.[2-4]

There has recently been significant effort to develop models and simulations for use in finite element analysis (FEA) in hopes of developing more reliable process planning and better understanding of the sheet forming process.[5-7] The models range from those using experimentally derived coefficients to those based theoretically on Amonton-Coulombs friction laws,[2] the Bay-Wainheim model,[8] or other numerically derived methods to account for the frictional effect.[9-13] Sowerby[13] and Yoon and his contemporaries[15] caution reliance on the accuracy of these models when addressing issues on friction.

In particular, there is a major interest in the role of galvanized surface layers in friction and lubrication behavior of sheet metals. Experiments by Zeng and Overby,[16] using specific lubrication and material conditions, show the coefficient of friction to be higher for galvanized steel than uncoated material. Work by Fox *et al.*[3] and Liu and Lee[4] shows a decrease in the coefficient of friction when galvanized steel is compared to nongalvanized steel under different test conditions. In work primarily geared to identifying relationships between lubricant type and galvanized steel, Meuleman and Dwyer[17] show that frictional effects of zinc coating are dependent on other process variables. Keeler[18] has done extensive work on the relationship between friction, galvanized steel, and bare steel under a wide variety of lubricating conditions. He shows, through detailed testing, that no generalization can be made about the behavior of coated steel. Results are dependent on the interacting relationship of coating, lubricant, die material, and drawing speed. He points out, in fact, in some instances, that there are significant differences in frictional behavior within a given set of conditions that are solely attributable to a difference in manufacturers of the same type of galvanized steel or lubricant.

The present work applies orthogonal array techniques of factorial testing[19] to ascertain general relationship between friction forces, lubrication techniques, die material, blank material, punch speed, and die radius. The experiments, based on original work by Swift,[21] were conducted using a tensile strip model similar to those used by Duncan,[22] Littlewood and Wallace,[23] Fox *et al.*[3] and Liu and Lee.[4] Doege and contemporaries give support to the use of such a model to experimentally define frictional effects.[24] A control experiment set, with all variables remaining constant except die radius, is included for comparative purposes.

2. Experimental Apparatus and Procedures

2.1 *Test System*

2.1.1 *Test Apparatus*

Force data must be collected to measure both front tension and back tension at various contact angles to develop friction coefficients. The design must also accommodate a wide variety of die radii, while maintaining the tensile strip in line with the crosshead of the test machine. Development of this test apparatus is based on previous works by Fox *et al.*,[3] Liu and Lee,[4] Duncan *et al.*,[22] and Littlewood and Wallace.[23]

The apparatus design provides interchangeable die wheels and mounting inserts. It incorporates frictionless (free spinning

D.P. Kotchman, I. Kim, and **D. Lee,** Department of Mechanical Engineering, Aeronautical Engineering and Mechanics, Rensselaer Polytechnic Institute, Troy, New York; and **C-Y. Sa,** Advanced Manufacturing Eng., General Motors Technical Center, Warren, Michigan.

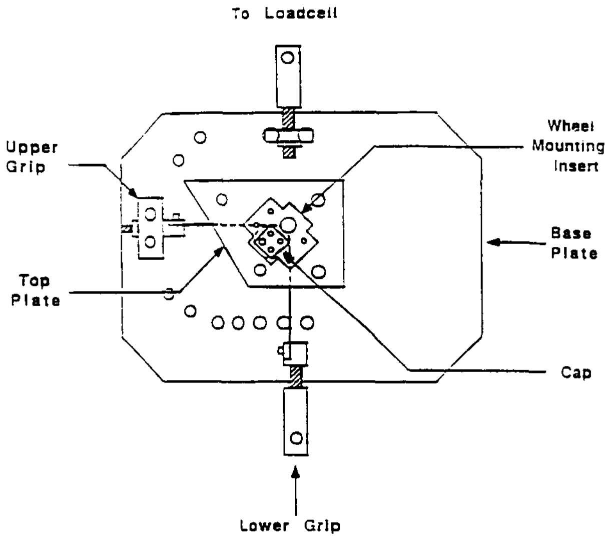

Fig. 1(a) Front view of testing apparatus.

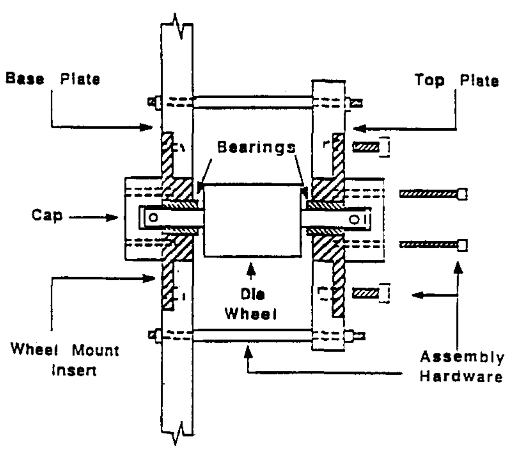

Fig. 1(b) Side view of testing apparatus.

die wheel) and frictional (pinned die wheel) conditions. A front view of the apparatus is shown in Fig. 1(a), and a side view is shown in Fig. 1(b). The apparatus has four main components: base plate, top plate, wheel support inserts, and wheel caps. The die attaches to an Instron testing machine loading frame. The design emphasizes balance of the apparatus in the loading frame, thereby minimizing any false bending effects on force readings. The present design allows for experiments to be conducted at angles of 45, 90, 135, and 180°. The base and top plate of the die have removable inserts. These inserts allow proper alignment of die wheels with the loading frame. Thus, the tensile strip remains aligned with the loading frame crosshead, and the applied forces remain in plane with tensile strips. Each wheel mounting hole is fixed with a rolling element bearing to simulate a frictionless environment when the die wheel spins freely. Caps mounted to each insert provide the base for pinning die wheels when modeling frictional conditions.

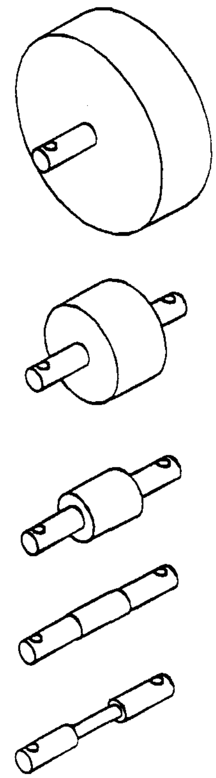

Fig. 1(c) Test dies.

2.1.2 *Die Wheels*

Three sets of die wheels of varying radii provide the bending and stretching surface for the test specimens. Each wheel set contains a 0.508-cm (0.2-in.), 1.102-cm (0.4-in.), 2.032-cm (0.8-in.) and 4.064-cm (1.6-in.) radius wheel, as shown in Fig. 1(c). Each set of die wheels is made of a different material. GM241 is a cast steel alloy with a hardness of 86 Rockwell B (HRB). GM311 and Kirksite are zinc-base alloys having hardnesses of 64 and 57 HRB, respectively.

2.1.3 *Data Acquisition System*

Tension measurements are processed digitally through a data acquisition system. Data acquisition is accomplished via a personal computer with an analog-to-digital converter. A set of computer programs monitor and sample test data. Front tension measurements are obtained directly from the Instron load cell as voltage changes and travels through the data acquisition system into a personal computer as binary code. Back tension readings are gathered using a series of electrical resistance strain gages mounted on the upper grip of the test apparatus. The voltage signal from the strain gage processes though a specially developed signal conditioner and amplifier.[3] The signal from the strain gage set is then sent through the data acquisition system to the personal computer for further processing. The test apparatus is set up in a 45,356-kg (10,000-lb) capacity Instron testing machine 4204 loading frame and control console. The entire test system is shown schematically in Fig. 1(d).

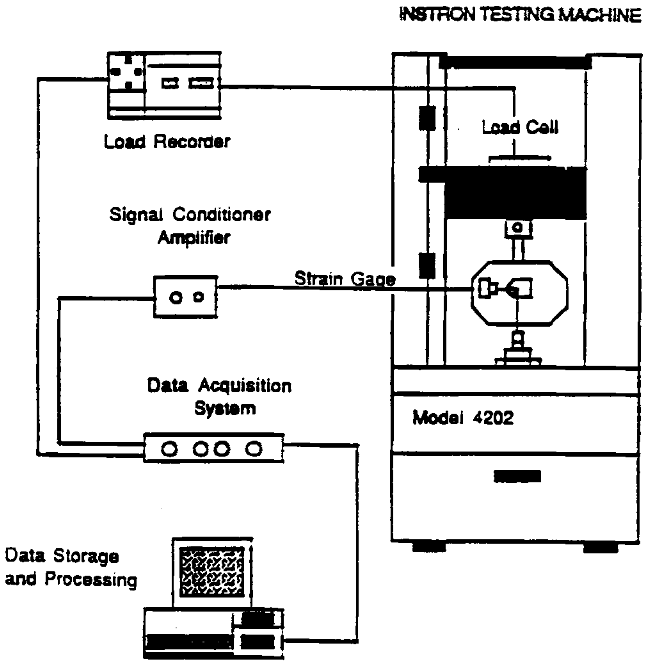

Fig. 1(d) Friction test system.

2.1.4 *Test Specimens*

Experiments are conducted using two test materials. The first is 0.0782-cm (0.0308-in.) aluminum-killed, drawing-quality steel (AKDQ). The second is 0.0787-cm (0.0310-in.) electrogalvanized aluminum-killed, drawing-quality steel (AKDQ-EG). The AKDQ-EG steel is electrogalvanized with zinc on both sides of the material. Machined specimens are 24.1-cm (9.5 in.) by 2.065-cm (0.813 in.) with a contact width of 1.588-cm (0.625 in.) parallel to within 0.013-cm (0.005 in.). All specimens are cut in the rolling direction.

2.2 *Lubrication*

The role of lubrication is examined by applying three diverse lubricating conditions. They consist of dry contact, a water-base oil emulsion, and polytetrafluororoethylene (PTFE). These lubrication conditions signify extremes in frictional behavior.

2.2.1 *Dry Conditions*

Dry experiments are intended to depict maximal friction conditions between the die and workpiece. Test results, however, are affected by a wide variety of conditions that are quite difficult to control. Continuously reproducing exact surface conditions is difficult. Room temperature and relative humidity can have significant impact on frictional conditions, as shown in work by Homola and contemporaries.[25] Reports by Schey[26] discuss the effects of surface film oxidation on friction and its tendency to act as a lubricating agent, thereby reducing friction effects. In these tests, temperature and humidity control are not precisely regulated. A centralized air conditioning system helps to maintain fairly consistent temperatures.

2.2.2 *Water-Base Emulsion*

The water-base emulsion used in this experiment is commonly referred to by its manufacturer's name, Montgomery 4285 (M4285). The major components of this lubricant consist of water (70%), paraffin oil (10%), cereclor (10%), fatty acids, tallow (10%), sodium salt (5%), fish oil (5%), and others (5%) by weight. The solution is prepared in a ratio of five parts water to one part M4285.

In the manufacture of sheet metal components such as automobile body panels, care must be taken to ensure that any lubricant applied to reduce friction in forming operations can be easily removed prior to painting operations. Failure to accomplish this results in lubricant filling asperities in the base metal. This precludes proper paint adherence to the bare metal and results in improper bonding of the paint to the body panel. As such, paint is more susceptible to running or peeling, resulting in a poor quality finish on the body panel.[26]

2.2.3 *Teflon (PTFE)*

Teflon PTFE is noted for its low shear strength and therefore as an excellent friction reducer. In certain applications, the resultant coefficient of friction can be as low as 0.004.[4] PTFE serves as an excellent solid film lubricant, precluding interaction between surface asperities in the workpiece and die. the PTFE strips are approximately 0.0104 cm (0.004 in.) thick and are cut to cover the entire possible contact surface between the die and tensile strip.

2.3 *Experimental Procedures*

Test procedures are designed to examine the effects of five parameters on the coefficient of friction found when a strip is drawn over a die. The parameters are die material, workpiece material, crosshead travel speed, lubricating condition, and die radius. All variables have been previously discussed with the exception of speed. Experiments are conducted in sets of eight, using speeds of 0.508, 5.08, and 50.8 cm/min (0.2, 2.0 and 20.0 in./min). This includes one test pinned and unpinned at each of the four mentioned angles.

2.3.1 *Test Matrix*

Conducting a full factorial experiment of all possible combinations of the five variables at four angles, pinned and unpinned, requires a total of 1728 experiments. Use of a partial factorial experimental method effectively reduces the number of required tests while still allowing effective examination of the impact of major variables. Several methods of partial factorial experimentation are available for use.[27] This experiment is based on the use of Taguchi T-18 orthogonal matrices.

The experiment uses two T-18 matrices. Parameters are varied between the two matrices to provide an overlap of some conditions of the experiment. This allows for comparison of conditions where only one variable of the experiment is changed. Comparison of the results of the two matrices finds that, for the 0.4 in. radius die wheel, the wheel common in both matrices, general friction coefficients vary by less than 0.2%. Table 1 contains the actual test matrices.

A control test set is used to provide comparative data based on changes in a single variable. Variation in die radius is chosen as the variable so that results of other previously mentioned works can be used in comparison of matrix data and control data. Table 2 summarizes the parameters of the control set.

2.3.2 *Specimen and Die Preparation*

Prior to loading test specimens into the test apparatus, certain procedures are necessary to ensure consistency in testing. Each test strip edge is carefully deburred. Failure to remove these burrs results in the creation of artificial asperities with orders of magnitude greater than those naturally found in the metal itself. These ridges serve as boundaries to trap fluid and prevent the normal squeeze of fluid film from the contact region when lubricated.

Specimens and die wheels are washed twice with acetone to remove residual lubricant from the manufacturing process and oily residue from handling. The acetone wash also removes any particular debris that may become deposited on the die wheel or test specimen.

Between each test, die wheels are polished using a 600-grit paper. This reconditions die surfaces after testing, because asperity flattening and metal deposition result during test runs. This is particularly true with the two softer die materials and when using AKDQ-EG steel for test strips. The transfer of metal between two objects in contact and its affects on friction are well documented.[17,18,24]

Table 1 Test Variable Factors

Factors	Level 1	Level 2	Level 3
Matrix A			
Workpiece	AKDQ	AKDQ-EG	...
Die material	GM241	GM311	Kirksite
Speed, in./min	0.2	2.0	20.0
Lubricant	Dry	M4285	PTFE
Die radius, in.	0.2	0.4	0.8
Matrix B			
Workpiece	AKDQ	AKDQ-EG	...
Die material	GM311	GM241	Kirksite
Speed, in./min	0.2	2.0	20.0
Lubricant	Dry	M4285	PTFE
Die radius, in.	0.4	0.8	1.6

Table 2 Control Test Set

Die radius, in.	Friction coefficient, μ
0.2	0.170 ± -0.005
0.4	0.070 ± -0.005
0.8	0.050 ± -0.005
1.6	0.040 ± -0.005

Note: Die material GM241; testing speed 2.0 in./min; lubricant M4285; test material AKDQ-EG.

2.3.3 *Procedures*

The test apparatus is attached to the crosshead of the Instron 4204 and the lower grip is mounted to the frame of the machine. The strain gage is mounted in the upper grip and moves with the main body of the test apparatus as the crosshead moves. Tests are conducted in sets of eight. The tensile specimen is bent around a die wheel in accordance with test matrix parameters. Starting at the 45 ° contact angle, pinned then unpinned, testing is done for progressively larger contact angles until a set is complete.

Prior to triggering the movement of the crosshead, a computer program is run that converts voltage signals being processed to the data acquisition system into force readings on the computer screen. This allows the operator to ensure proper and consistent readings for both front and back tension at the start of a test.

2.3.4 *Calculation of the Friction Coefficient*

Figure 2 illustrates the force relationships found during the test.[3] The angular arc of contact is designated by θ. T_{1a} represents the applied forward tension and T_2 the resulting back tension. T_{1b} is the forward tension due to bending and unbending effects. F_n is the normal force applied to the center of the arc of contact, and μ is the coefficient of friction. Allowing dF_n to be the incremental normal force, a balance of forces results in the following relationship:[4]

$$\mu = (1/\theta)\ln\left[\frac{T_{1a} - T_{1b}}{T_2}\right] \quad [1]$$

The test strip thickness to die radius ratio is small, 0.15 at the smallest radius. The sheet metal strip can therefore be considered to undergo shear deformation equally across its thickness. Were this not the case, and a shear stress profile existed in the material, then multiplying the coefficient of friction by the ratio of the radius to the centerline of the test strip (R_c) to the inner radius of the test strip (die radius, R) results in the correct μ.

The unpinned version of each pair of tests is used to measure the bending and unbending forces found at each angle. Because

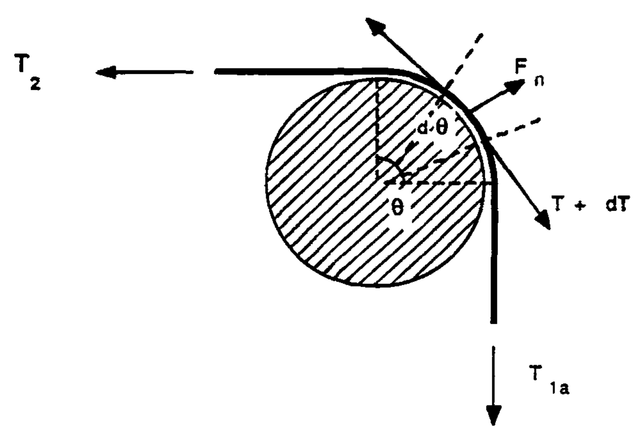

Fig. 2 Force relationships in strip testing.

the unpinned version of the experiment represents a frictionless condition, Eq 1 yields the following relation:

$$T_{1b} = T_{1a} - T_2 \quad [2]$$

The pinned version of the experiment is conducted in the same manner as the unpinned. Because the die wheel is now rigid, the test specimen is forced to strain over the contact radius of the wheel. Again, both front and back tension readings are collected. Front tension due to stretching can be calculated by subtracting the front tension due to bending from Eq 2, T_{1b}, from the front tension reading in the pinned test, T_{1a}. Therefore, the front tension due to stretching, T_1, is defined as $T_1 = T_{1a} - T_{1b}$. The friction coefficient is read directly as the slope of the line formed when the natural logarithm of T_1/T_2 is plotted against the contact angle after a linear curve fit is applied to the data.

3. Results and Discussions

Results of experiments with respect to the variables for galvanized and nongalvanized sheet show a consistent relationship with previously documented experiments of this type. Additionally, results fall within the range of other predictive and experimental friction models. Due to the significant impact lubrication has on the standard deviation of the data, results are separated by lubricating condition. The effect of separate lubricating conditions is easily identifiable across the broad spec-

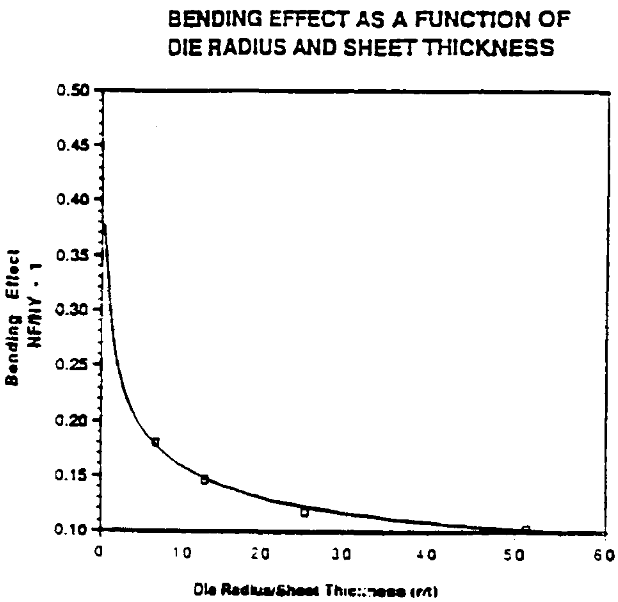

Fig. 3(a) Bending effect relationship to die radius.

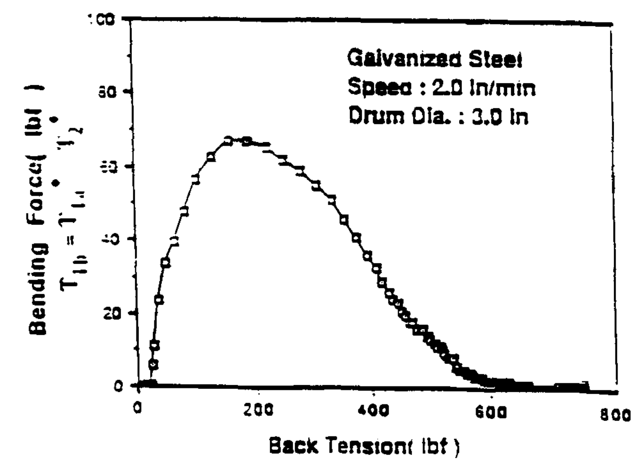

Fig. 3(b) Bending effect relationship to back tension.

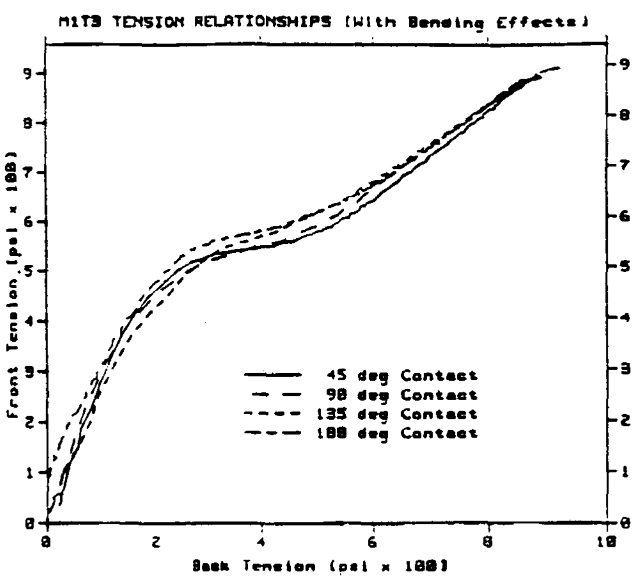

Fig. 4(a) Plot of front versus back tension (pinned) with bending effect.

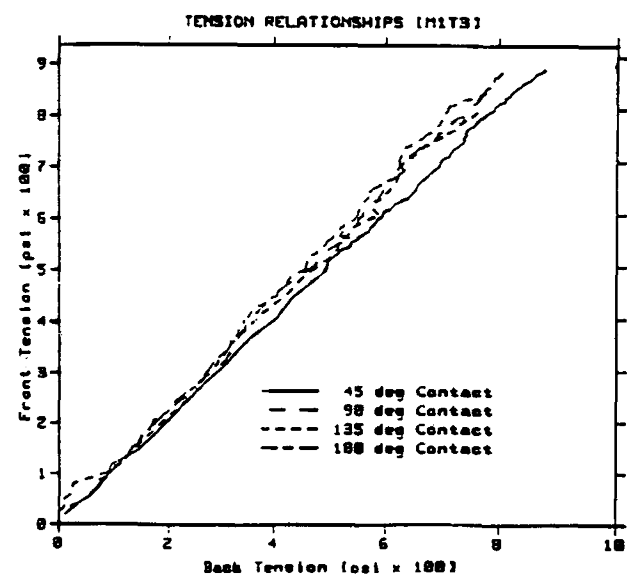

Fig. 4(b) Plot of front versus back tension (pinned) without bending effect.

trum of results. No such relationships exist for the interaction of other variables, and therefore, further separation of interacting variables could not be accomplished. Tables 3,4,5, and 6 represent the various matrix combinations and summary of the friction coefficient values.

Individual test results reveal some limitations in the capabilities of the test apparatus design. Two sets of tests could not be performed because of failure of the 0.2-in. radius Kirksite die wheel when run at 20.0 in./min under dry conditions. Cause for this failure can be attributed to stress concentrations at the interface of the die wheel and mounting shaft. As a result, there possibly exists minor deflection due to elastic deformation in other die wheels of this material. This may have had an influence on resultant friction coefficient determinations.

The bending effect response follows predicted patterns. The bending effect is greatest at the smallest die radius. Lubricating conditions appear to have no significant effect on the magnitude of the bending effect. This is evident by the consistency in the bow of the T_1/T_2 curve between 0.0 and 600 lb force for constant die radii and varying lubrication scheme and die material. The influence of bending is plotted as the difference between the front and back tension, normalized to the back tension (T_{1a} - T_2)T_2, versus the ratio of the die radius to the sheet thickness. Relations follow the general trend illustrated by Werner.[28] An example of the reduced test data is shown in Fig. 3(a).

3.0.1 *Calculation of Friction Coefficients*

Friction coefficient data are determined as discussed previously. The front and back tension readings obtained from the original unpinned experiment are used to obtain values for T_{1b}. Plotted against the back tension, T_{1b} is represented by Fig. 3(b). The pinned version of the test is completed, and the resultant data take the form of a plot of front tension (T_{1ap}, to back tension (T_2). This curve, prior to the removal of the bending/unbending effect, is depicted in Fig. 4(a). The large bow in the curve represents the bending effect. The results of the bending/unbending effect, T_{1b}, are removed from T_{1a} and plotted as T_1 versus T_2 for all contact angles on the same plot, as shown in Fig. 4(b). Notice that the curve is now much more linear, as expected for a constant coefficient of friction. An example of the reduced test data and the resulting friction coefficient (slope) is shown in Fig. 5(a).

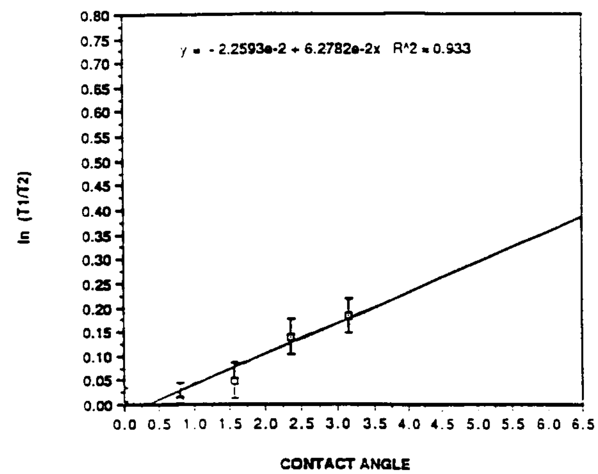

Fig. 5(a) Plot of $\ln(T_1/T_2)$ versus θ.

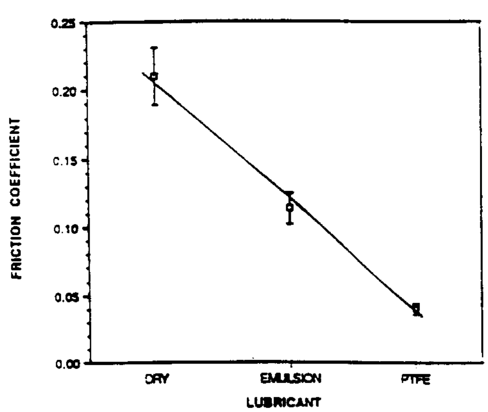

Fig. 5(b) Lubricant effects on friction.

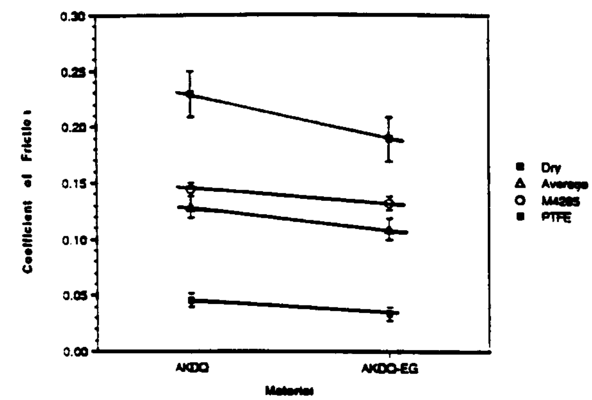

Fig. 5(c) Friction coefficients in galvanized and bare steel.

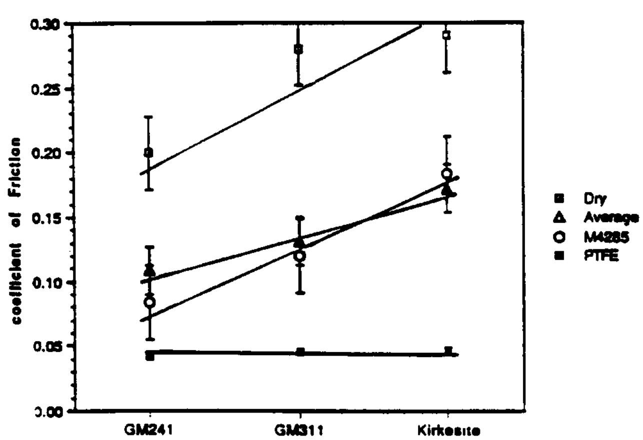

Fig. 5(d) Die material effects on friction coefficients.

3.1 *Effect of Variables on Friction Coefficients*

3.1.1 *Lubricating Condition*

There is a strong general relationship for varying lubrication techniques. The mean values for dry, liquid, and solid film (PTFE) lubrication, as shown in Fig. 5(b), are consistent with previously referenced work. As expected, the reduction in friction coefficient is greatest for PTFE. This correlates well with the fact that PTFE prevents asperity contact between die and workpiece.

The results for M4285 are evidence of lubrication by mixed film lubrication. Results from these tests fall into the region commonly associated with mixed film lubrication.[2] Consistent evidence of asperity contact, via deformation of the die wheel or workpiece through the mechanism of adhesive wear, routinely manifests itself as solid debris or wear marks.

3.1.2 *Tensile Strip Material*

Evaluation of test materials indicates a lower coefficient of friction for galvanized steel than for bare steel. The results are summarized in Fig 5(c). The difference in friction coefficients of 0.046 falls in line with work by Keeler,[18] where a difference of 0.04 is indicated for similar material conditions. Note that in all lubrication conditions, the galvanized steel had a lower coefficient of friction than bare steel. Although only appropriate for these specific test parameters, it can be attributed to the tendency of the zinc floating to act as a solid film lubricant when in contact with the much harder die wheel for dry contact. In liquid lubrication, galvanized steel again exhibits better friction resistance than bare steel. The increased porosity of the zinc coating compared to bare steel supports more pockets of liquid. Therefore, more load is distributed through the shear of the liquid. The resultant forces acting against the asperities from pressure in the lubricant pockets delay plastic deformation of the coating, and friction forces are reduced.

Table 3 Test Variable Factors I

Factors	Level 1	Level 2	Level 3
Workpiece	AKDQ	AKDQ-EG	...
Die material	GM241	GM311	Kirksite
Speed, in./min	0.2	2.0	20.0
Lubricant	Dry	M4285	PTFE
Die radius, in.	0.2	0.4	0.8

3.1.3 *Die Material*

Results show that friction coefficients obtained from different die materials respond as predicted in the adhesion theory. The friction coefficient is increased as the material hardness decreases. Note that in Fig. 5(d) this can be shown for both the dry and M4285-lubricated conditions. However, the coefficient of friction remains relatively constant for the PTFE-lubricated condition. The increase in friction coefficient for the M4285-lubricated condition further supports the mixed film theory of lubrication for the fluid condition where asperities do come in contact with each other.

In the PTFE-lubricated conditions, however, the die and workpiece materials never reach asperity contact. Therefore, the coefficient of friction is a function of the shear strength of the PTFE sheet rather than the material hardness. The value of approximately 0.045 for μ compares favorably with values of μ determined in previous efforts.[28]

3.1.4 *Speed Effect*

There appears to be no strong relationship of speed within the tested range as a result of these experiments. This contradicts work done by several others authors.[4,21,16,29,30] One possible reason for this is that the effects of speed cannot be easily unhinged from other interacting variables such as lubrication or

Table 4 Test Variable Matrix I and Measured μ

Test No.	Workpiece	Die material	Speed	Lubricant	Die radius	Measured μ
1	1	1	1	1	1	0.18 ± 0.01
2	1	1	2	2	2	0.12 ± 0.01
3	1	1	3	3	3	0.04 ± 0.01
4	1	2	1	1	3	0.21 ± 0.01
5	1	2	2	2	2	0.11 ± 0.01
6	1	2	3	3	1	0.10 ± 0.01
7	1	3	1	3	1	Failed
8	1	3	2	2	2	0.13 ± 0.01
9	1	3	3	1	3	0.18 ± 0.01
10	2	1	1	3	3	0.04 ±0.01
11	2	1	2	1	1	0.28 ± 0.01
12	2	1	3	2	2	0.12 ± 0.01
13	2	2	1	3	3	0.03 ± 0.01
14	2	2	2	2	1	0.12 ± 0.01
15	2	2	3	1	2	0.24 ± 0.01 (0.34)(a) ± 0.01
16	2	3	1	3	2	0.06 ± 0.01
17	2	3	2	1	3	0.06 ± 0.01
18	2	3	3	2	1	0.13 ± 0.01

(a) Based on GM311 die wheel, 0.4-in. radius and dry condition. The initial test indicated by ( ) showed deflection of shaft. Repeated with tool steel shaft.

die material. The mean values are based on a substantial number of variables. If speed has conflicting effects on different variables, no clear conclusion can be derived.

3.1.5 *Die Radius*

The general effect of a decreasing die radius is an increase in the coefficient of friction. The mean results of all tests indicate this relationship, as shown in Fig.6(a). Taken a step further, and broken down by lubricant category, it can be seen the same trend apparently holds true. For dry friction and liquid lubrication, the decrease in friction appears to follow a smooth path. However, μ for PTFE appears to make a more dramatic drop between the 0.2- and 0.4-in. radius die and then stabilizes.

Examination of individual tests for PTFE seems to indicate that larger diameter wheels have a much low coefficient of friction than smaller diameter ones when run at the same speed. The standard deviation of data points making up the mean value of μ for all speeds, at each radius, is lower than the one for the total data for the 0.2-in. radius die. The removal of the 0.2-in radius die under a load speed of 20.0 in./min brings the mean and standard deviation of μ in line with other results.

In the control experiment set, a similar trend is observed, although somewhat more extreme in curvature. The results for dry conditions compare favorably with experiments conducted by Zeng and Overby[16] for the case of dry friction, as shown in Fig. 6(b). It is based on an average of the data of Zeng and Overby for both galvanized and nongalvanized material so as to reflect similar conditions.

Table 5 Test Variable Factors II

Factors	Level 1	Level 2	Level 3
Workpiece	AKDQ	AKDQ-EG	...
Die material	GM311	GM241	Kirksite
Speed, in./min	0.2	2.0	20.0
Lubricant	Dry	M4285	PTFE
Die radius, in.	0.4	0.8	1.6

4. Summary and Conclusions

Use of orthogonal matrices to develop friction relationships provides a robust tool for evaluating general effects of several variables on the coefficient of friction. Observed results are consistent with data reported by others. Use of matrices provides a means to identify critical variables on the coefficient of friction so that experimentation and analysis can be concentrated in areas considered the most significant. Results from the orthogonal matrix cannot be used to specify effects due to interaction of individual variables on the coefficient of friction. The inability for the effect of speed to be adequately addressed and the variation between the control group and matrix results for varied die radius are evidence of this limitation.

Lubricant and die material play the most significant role among factors examined in determining the coefficient of friction. Test results show an increase in μ with a decrease in die hardness consistent with the adhesion theory of friction. Liquid lubrication predominantly follows the mixed film mechanism, as indicated by the continued influence of material hardness on friction. M4285 is an effective lubricant for both bare steel and galvanized steel, with little difference in the coefficient of friction between the two because the fluid film bears a large portion of the normal load and the resultant forces in the lubricant pockets delay asperity flatting of the zinc coating. PTFE is the most effective lubricant tested and provides the most uniform results regardless of other factors.

Die radius has a pronounced effect on the coefficient of friction. A decrease in die radius generally increases the coefficient

Table 6 Test Variable Matrix II and Measured μ

Test No.	Workpiece	Die material	Speed	Lubricant	Die radius	Measured μ
1	1	1	1	1	1	0.21 ± 0.01 (0.35)(a) ± 0.01
2	1	1	2	2	2	0.15 ± 0.01
3	1	1	3	3	3	0.04 ± 0.01
4	1	2	1	1	3	0.23 ± 0.01
5	1	2	2	2	2	0.06 ± 0.01
6	1	2	3	3	1	0.06 ± 0.01
7	1	3	1	3	1	0.03 ± 0.01
8	1	3	2	2	2	0.04 ± 0.01
9	1	3	3	1	3	0.22 ± 0.01
10	2	1	1	3	3	0.06 ± 0.01
11	2	1	2	1	1	0.21 ± 0.01
12	2	1	3	2	2	0.12 ± 0.01
13	2	2	1	3	3	0.02 ± 0.01
14	2	2	2	2	1	0.12 ± 0.01
15	2	2	3	1	2	0.12 ± 0.01
16	2	3	1	3	2	0.06 ± 0.01
17	2	3	2	1	3	0.11 ± 0.01
18	2	3	3	2	1	0.14 ± 0.01

(a) Based on GM311 die wheel, 0.4-in. radius and dry conditions. The initial test ( ) showed deflection of shaft. Repeated with tool steel shaft.

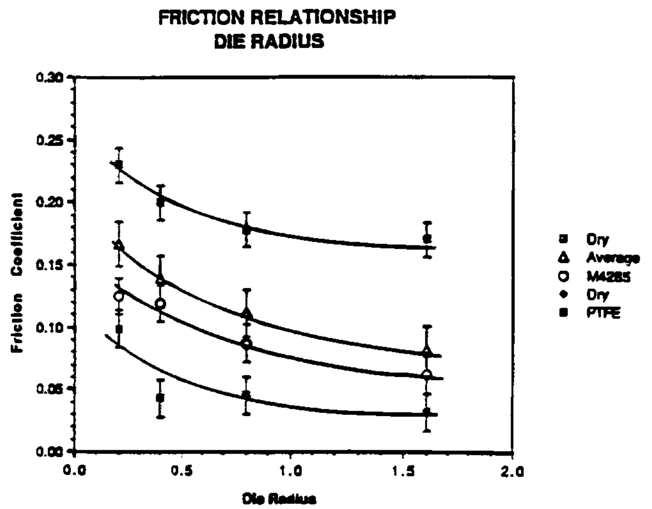

Fig. 6(a) Effects of die radius on friction.

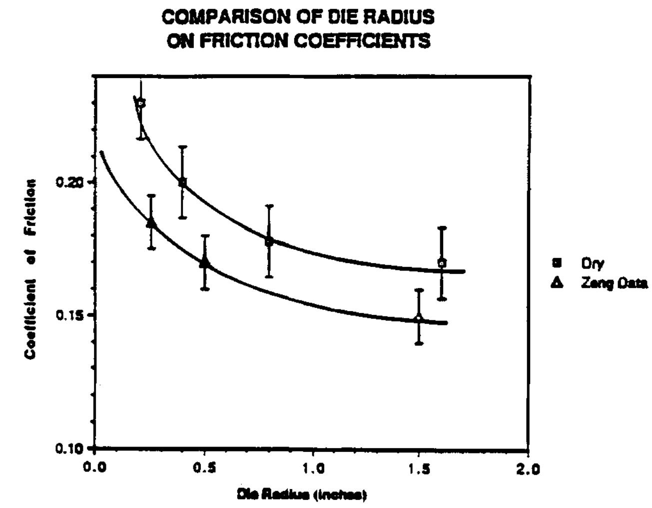

Fig. 6(b) Comparison of die radius effects with experiments performed by Zeng and Overby.[16]

of friction across all lubricating conditions. The influence of die radius on μ appears regardless of lubrication scheme and is reinforced by the results of the control set of experiments. Similarly, the bending effect increases with a decreasing die radius to sheet thickness ratio. One possible correlation is that increased bending and unbending over a small die radius, combined with increased sliding over that radius, increases the coefficient of friction.

Sheet material has a less pronounced effect on μ. In dry contact, galvanized steel has a lower coefficient of friction than bare steel; a result of the tendency for the zinc coating to break its bond with the base metal and serve as a solid lubricant. Contrary to other efforts of this nature, crosshead speed appears to have no significant effect on the coefficient of friction within the range tested. It is quite possible that the interaction of other variables masked the effect of speed when examined as part of the orthogonal matrix.

Use of the tensile strip method for determining friction coefficients provides reasonable results when compared to existing data on various testing schemes. Use of orthogonal arrays to evaluate friction coefficients is proven to be effective.

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