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Technical Note: A New Test Procedure for the Bending under Tension Friction Test

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RECENT developments in coated sheet metals, *e.g.*, galvanized or prepainted sheet steels for automotive components, and the application of computer modeling to analyze forming operations have necessitated an improved understanding of the frictional behavior between sheet metals and die materials. Several laboratory tests[1-9] have been used to measure friction. In most tests, Coulombic friction is assumed, *i.e.*, the friction coefficient μ is constant and described by:

$$\mu = \frac{F_s}{F_n} = \frac{\tau}{p} \qquad [1]$$

where F_s is the shear force between the sheet and the die, F_n is the normal force, τ is the interfacial shear stress, and p is the average contact pressure. The various laboratory friction tests incorporate different geometries, methods of load application, degrees of substrate strain, *i.e.*, elastic or plastic, testing speeds, and lubrication conditions. One test method that has received considerable attention is the bending under tension test.[1,8] This Technical Note presents a new method for performing the bending under tension test, along with a critique of data analysis methods.

In the bending under tension test, the friction coefficient is determined from measured force data by sliding a strip over a cylindrical roll, as shown schematically in Fig. 1. The bending under tension test is performed in a two-step process. First, a strip is drawn over a freely turning roller, and the force due to bending and unbending, F_b, is determined as the difference between the pulling and back tension forces, F_1^* and F_2^*, respectively. A second strip is then drawn over a fixed roller, and the corresponding pulling and back tension forces, F_1 and F_2, are determined. Several equations, each derived from a different set of basic assumptions, have been developed to determine μ from the set of four measured forces in a bending under tension test.[1] For a 90° bend angle, μ can be determined from:[1,8]

$$\mu = \frac{2}{\pi}\left(\frac{r + 0.5t}{r}\right)\ln\left(\frac{F_1 - F_b}{F_2}\right) \qquad [2]$$

where r is the roll radius, and t is the sheet thickness.

To date, reported friction test data have been obtained with bending under tension friction test systems configured with an adjustable, but constant, back force (*i.e.*, F_2 in Fig. 1) system, in which force data are measured and averaged over a period of time or displacement. To obtain statistically significant values of μ, two procedures have been used: (1) perform multiple tests at a constant back force and average the calculated μ values or (2) obtain data over a range of F_2 values, which corresponds to a range in contact pressures,[8] plot the results as $F_1 - F_b$ versus F_2, and calculate μ from the slope of the graph (*i.e.*, the ln argument in Eq 2). The second method is preferable.[9]

As an alternate method to constant back force tests, a new test method is proposed, in which all required force data for Eq 2 can be obtained from a single sample pair by linearly increasing the back force with strip displacement. The bending under tension test system described previously,[1] with servo hydraulic control systems for both the displacement rate and back force, was used to evaluate the friction behavior of a 0.05 wt.% carbon, 0.29 wt.% manganese drawing-quality uncoated sheet steel with the following properties: σ_y = 201 MPa (29.1 ksi), ultimate tensile strength = 316 MPa (45.9 ksi), e_T = 38.8%, t = 0.71 mm. Strip samples 305 by 50.8 mm were sheared with the long dimension parallel to the rolling direction, lubricated with a mineral seal oil,[10] and tested at a displacement rate of 42.3 mm/sec (100 in./min).

To evaluate the applicability of the increasing back force bending under tension friction test, force data were obtained with the back force either constant or linearly increasing with displacement. Examples of free and fixed roller force data for a constant back force test and for a linearly increasing back force test are shown in Figs. 2 and 3, respectively. All data are plotted

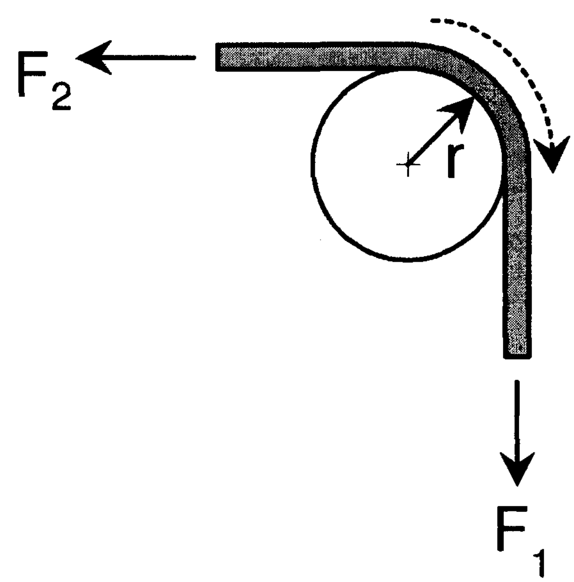

Fig. 1 Schematic of the bending under tension friction test.[8]

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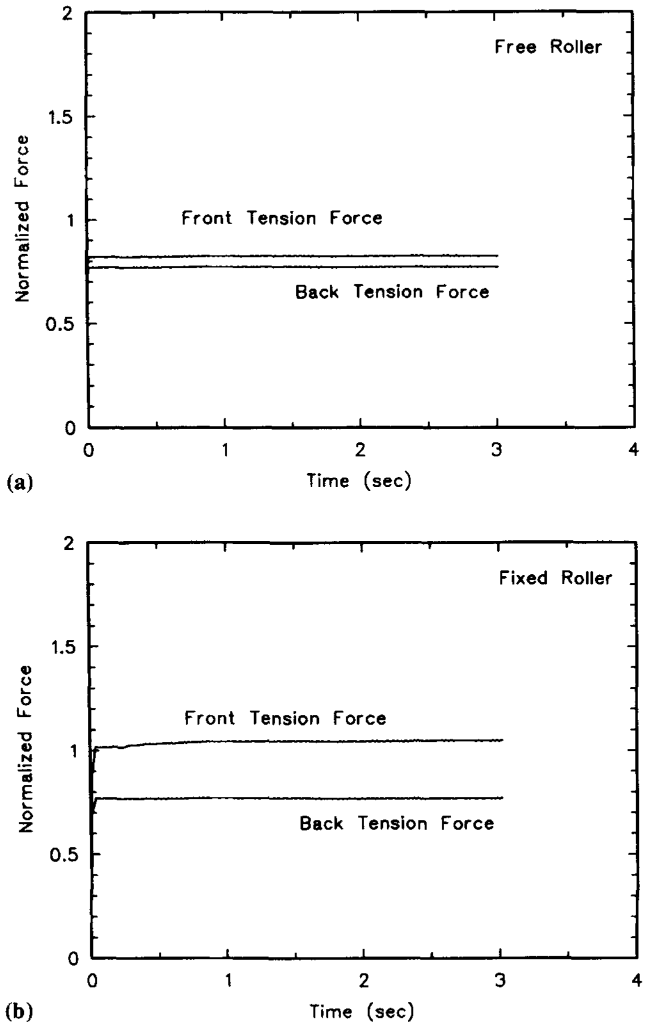

Fig. 2 Normalized force-time data obtained with the bending under tension test using constant back force control. (**a**) Free roller data. (**b**) Fixed roller data.

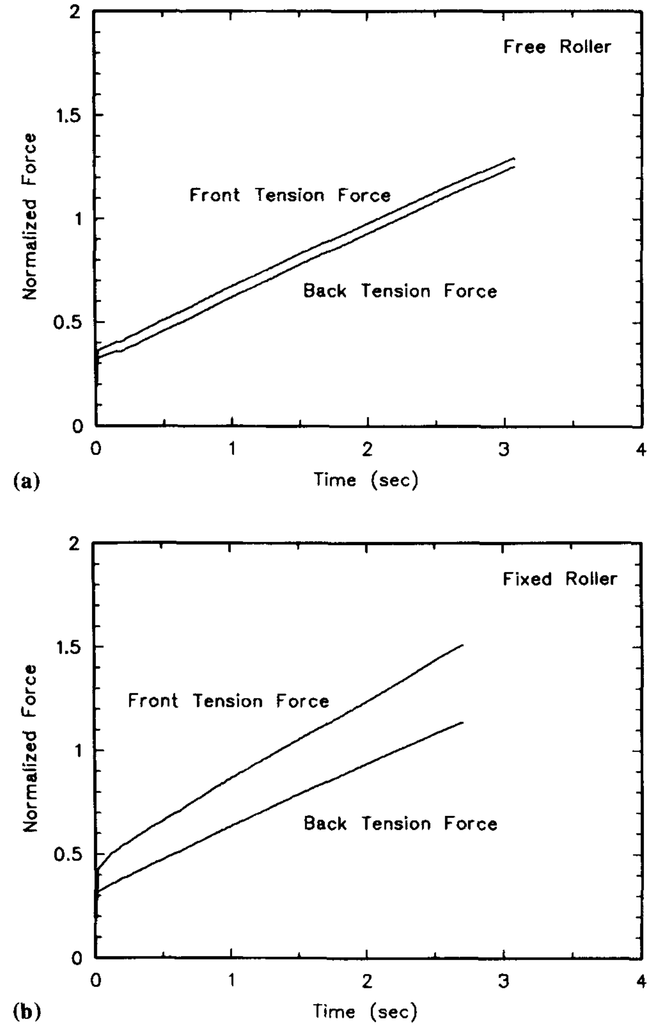

Fig. 3 Normalized force-time data obtained with the bending under tension test using a linearly increasing back tension force. (**a**) Free roller data. (**b**) Fixed roller data.

as normalized forces, in which measured forces are divided by F_y, the strip tensile yield load of 7.23 kN (1625 lb) calculated from the yield strength. Normalized force values greater than 1.0 indicate strip yielding in the free ligaments that are not in contact with the roller. In Fig. 2, the forces are constant within ± 27 N (± 6 lb). The increasing back force data in Fig. 3 are essentially linear.

Constant back force data from 15 sample pairs were plotted as normalized adjusted pulling force, $(F_1 - F_b)/F_y$, versus the normalized back force, F_2/F_y, as shown in Fig. 4. From the free roller data, F_b/F_y was constant over the entire force range and was equal to 0.052 (normalized value that corresponds to F_b of 374 N, or 84 lb). The data in Fig. 4, constrained to extrapolate through the origin,[1,10,11] describe a linear function which indicates that the friction coefficient is constant over the entire pressure range. From the slope of the line and from Eq 2, μ was determined to be 0.17.

The normalized force data from one sample pair (fixed and free roller) tested with an increasing back force are shown in Fig. 5. A normalized bending force of 0.048, a value representing the average of three increasing load free roller tests, was used. As in Fig. 4, the data describe a straight line, from which it was determined that μ is 0.17. The results shown in Fig. 4 and 5 indicate that the friction coefficients from the two test methods are equivalent.

The variability in friction coefficients, as measured with the procedure shown in Fig. 5, was considered by performing five identical increasing back force tests, and the results for each test, in the form of linear regression equation coefficients, and the calculated friction coefficients are summarized in Table 1. Corresponding data for the multiple sample plot of Fig. 4 are also included in Table 1. Within experimental accuracy, all tests produce the same friction coefficient (*i.e.*, a value between 0.16 and 0.17) and are equivalent to the result obtained from Fig. 4 with multiple tests. The degree of linear fit as described by the regression coefficient, R^2, was better than 0.9995 in all cases.

The results of this study suggest that, by using a test system with a linearly increasing back force, the number of samples required to obtain friction coefficients from a bending under tension test can be significantly reduced. The analysis assumes

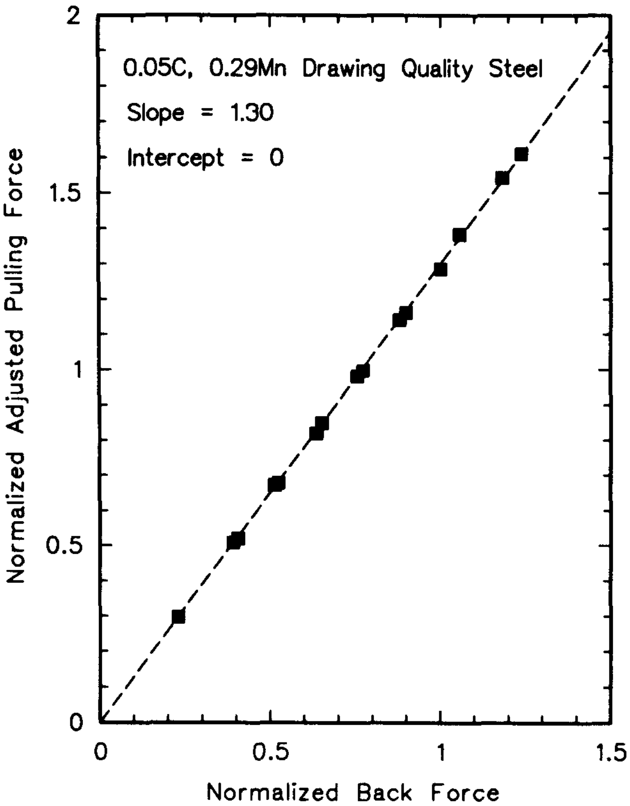

Fig. 4 Constant back force data from 15 data pairs (*i.e.*, free and fixed roller tests) plotted as normalized adjusted pulling force versus normalized back force. The linear function is constrained through the origin; the slope is indicated.

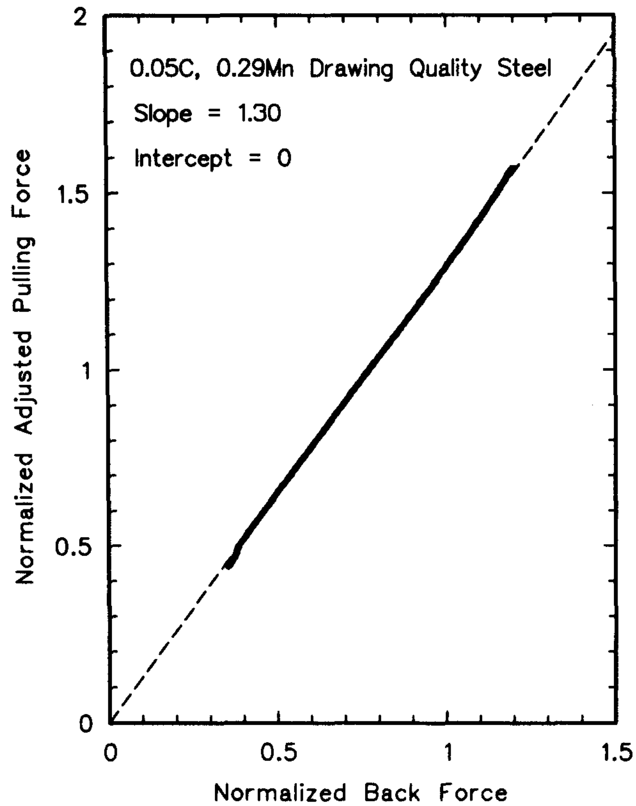

Fig. 5 Normalized adjusted pulling force versus normalized back force obtained from one sample pair (*i.e.*, one free and one fixed roller test) with the increasing back force test. The linear function is constrained through the origin; the slope is indicated.

Table 1 Summary of Bending under Tension Test Data Based on the Analysis Procedure which Requires Both Fixed and Free Roller Force Measurements

Test type	Test No.	Linear function slope	Normalized bending force(a)	Friction coefficient (μ)
Constant back force(b)	...	1.30	0.052	0.17
Increasing back force	1(c)	1.30	...	0.17
	2	1.29	...	0.16
	3	1.28	0.048(d)	0.16
	4	1.28	...	0.16
	5	1.29	...	0.16

Note: The bending force, F_b, is subtracted from the pulling force, and the plot of $F_1 - F_b$ versus F_2 is constrained to extrapolate through the origin. **(a)** Free roller data. **(b)** From Fig. 4. **(c)** From Fig. 5. **(d)** Bending force represents an average of three free roller increasing load tests.

that μ is independent of contact pressure. The degree to which this assumption is satisfied is indicated by the degree of linearity in the force data.

Recently[12] an additional data analysis procedure, which uses only fixed roller data, has been suggested as a method to further decrease the number of samples required to obtain μ. Specifically, if the Coulombic friction assumption is valid, a plot of F_1/F_y versus F_2/F_y should produce a straight line with a slope equal to $(F_1 - F_b)/F_2$ and an intercept equal to F_b/F_y. To evaluate the applicability of this data analysis method, the data for both the constant back force tests and for the increasing back force tests were re-evaluated considering only the fixed roller data. Plots of F_1/F_y versus F_2/F_y for the constant back force data considered in Fig. 4 and for the increasing back force data in Fig. 5 are presented in Figs. 6 and 7, respectively. The linear equation coefficients for the data are indicated in the fig-

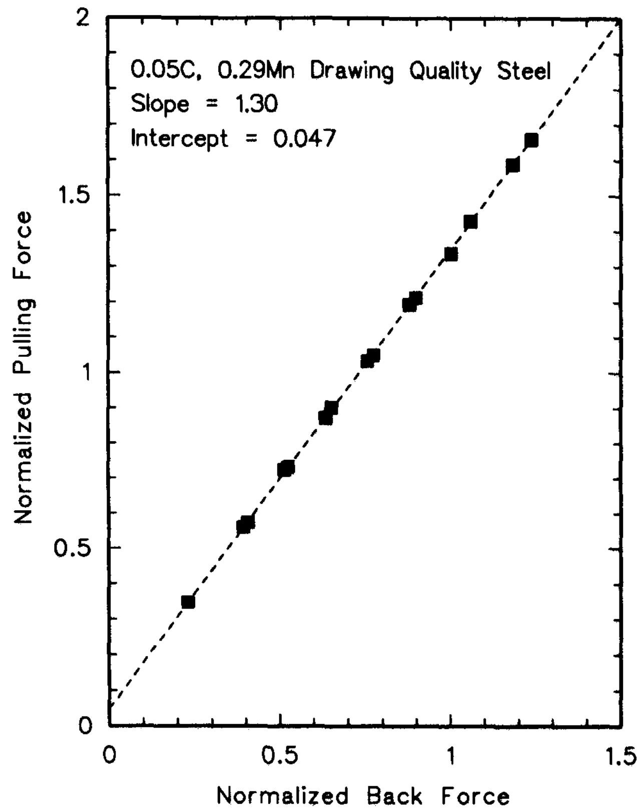

Fig. 6 Constant back force data from 15 fixed roller tests plotted as normalized pulling force versus normalized back force. The data describe a straight line not constrained through the origin; the slope and intercept are indicated.

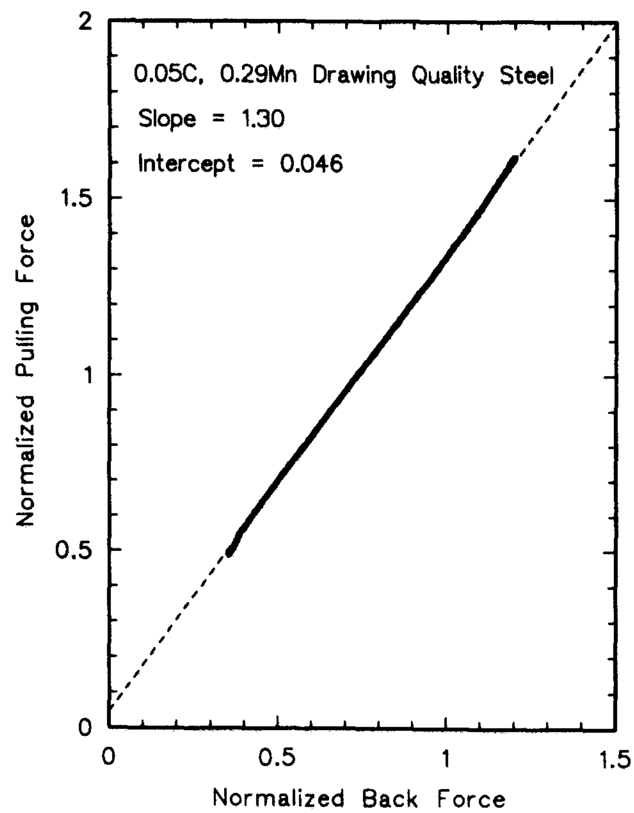

Fig. 7 Normalized pulling force versus normalized back force obtained from one fixed roller sample with the increasing back force test. The data describe a straight line not constrained through the origin; the slope and intercept are indicated.

Table 2 Summary of Bending under Tension Test Data Based on the Analysis Procedure which Requires Only Fixed Roller Data

Test type	Test No.	Linear function slope	Normalized bending force(a)	Friction coefficient (μ)
Constant back force(b)	...	1.30	0.047	0.17
Increasing back force	1(c)	1.30	0.046	0.17
	2	1.28	0.052	0.16
	3	1.28	0.050	0.16
	4	1.28	0.050	0.16
	5	1.28	0.053	0.16

(a) From linear intercept. (b) From Fig. 6. (c) From Fig. 7.

ures. The linear equation coefficients for the five tests discussed in conjunction with Table 1 are summarized in Table 2 with calculated friction coefficients. Also included in Table 2 are corresponding data from Fig. 6. The friction coefficients are equivalent to those obtained above. Thus, for the uncoated sheet steel of this study, the results from Fig. 7 indicate that it is possible to obtain a value of the friction coefficient from a single strip.

This study has indicated that additional procedures and data analysis methods can be incorporated with the bending under tension friction test to decrease the number of samples required to obtain valid friction coefficients. It should be noted, however, that the increasing back force test should be used with caution to ensure that the data are linear. In addition, data analysis with only fixed roller test data should be used only if it can be independently verified that the y-intercept is equal to the bending force. Applicability of the increasing back force test to coated sheet steels, in which friction conditions may change with contact pressure, is currently under study.

Acknowledgments

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