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Effect of Coating Characteristics on Friction and Formability of Zn-Fe Alloy Electroplated Sheet Steel*

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The effects of coating composition and coating weight on friction characteristics and formability under different deformation modes, as well as their mechanisms, were studied on zinc-iron electroplated drawing-quality special-killed (DQSK) sheet steels. Friction tests, simulative formability tests, and coating characterization were performed. The experiments revealed that the iron concentration of the coating has a tremendous effect on friction in the deep-drawing operation, but only a slight effect in the stretching operation. Uniaxial tension tests indicated that both coating weight and coating composition affect *n*-value and *r*-value. The dependence of friction characteristics, *n*-value, and *r*-value on iron concentration is related to the variation of coating hardness caused by the variation of iron concentration in the coating.

Keywords
coating, formability, friction, steel, Zn-Fe

1. Introduction

ELECTROPLATED zinc-iron alloy coatings (e.g., Ref 1) on sheet steels are used for exposed automobile panels because of their excellent corrosion resistance after painting and relatively long electrode life in spot welding (Ref 2-4). The coating properties can be altered by varying the iron concentration in the alloy. In order to optimize the forming performance of zinc-iron-coated steels, the iron concentration should be chosen so that both powdering and coefficient of friction are low during forming. Studies have shown that powdering of electroplated zinc-iron coatings increases with increasing iron concentration (Ref 3, 5). However, few studies have explored the effect of coating iron concentration on friction characteristics and formability under different deformation modes.

Low iron concentration has been suspected to have caused splits in sheet during stamping. Tension test evaluations have indicated that certain coatings may also reduce the work-hardening exponent (*n*-value) and the normal anisotropy or plastic strain ratio (*r*-value) (Ref 6-8). This paper addresses the effects of coating composition and coating weight on friction and tensile properties and the impact of these effects on formability under different deformation modes.

2. Materials

Electro zinc-iron alloy coatings with average iron concentrations of 8, 12.5, and 18% were deposited by a laboratory circulation cell (Table 1). Variation of iron concentration from the average values was about ±1.5%. Two coating weights, 35 and 55 g/m^2, were plated so that the effect of coating thickness on coefficient of friction and formability could be studied. The substrate panels for different coatings had the same mechanical properties and thickness (0.034 in.) because all were from the same location of a commercial coil of a drawing-quality special-killed (DQSK) sheet steel. The surface topographies for all coatings were also similar (Table 1 and Fig. 1). Therefore, the only significant variables were coating composition and coating weight. These samples are designated as lab-coated steel in the following discussion.

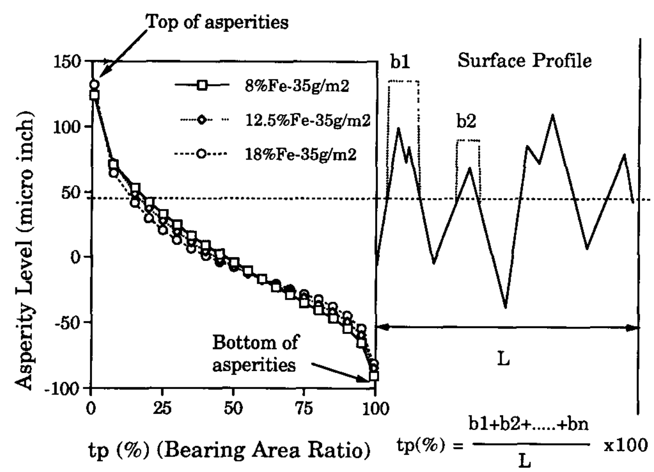

Fig. 1 Bearing area ratio of the original surface of lab-coated steels

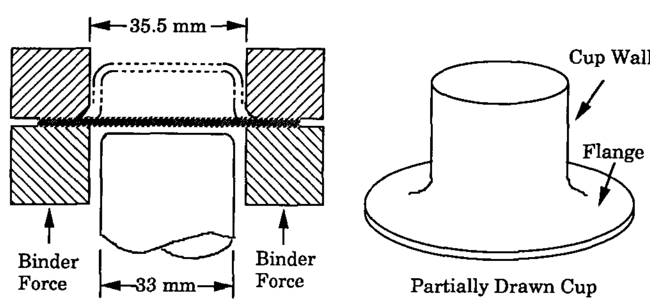

Fig. 2 Draw cup test

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Table 1 Coating characteristics of lab-coated steels

Characteristic(a)	Sample coating weight, g/m² 8% Fe 35	8% Fe 55	12.5% Fe 35	12.5% Fe 55	18% Fe, 35
R_a, μin.	37.6	33.7	35.0	31.0	31.8
R_{max}, μin.	234	227	213	205	220
P_c, peak/in.	131	143	129	113	112

(a) R_a, average roughness; R_{max}, maximum roughness depth; P_c, peak count

Table 2 Coating characteristic of plant-coated steels

Characteristic	Sample coating weight, g/m² 12% Fe, 50	14% Fe, 50	18% Fe, 50
R_a, μin.	28.2	28.3	27.7
R_{max}, μin.	175	272	130
P_c, peak/in.	162	84	115

Table 3 Coefficient of friction for lab-coated steels

Coating weight, g/m²	Coefficient of friction 8% Fe	12.5% Fe	18% Fe
35	0.15	0.14	0.14
55	0.16	0.14	...

Note: Standard deviation = 0.01; pulling speed, 20 in./min; die radius, 0.375 in.

In addition to the laboratory prepared samples, zinc-iron alloy coatings with iron concentrations of 12, 14, and 18% were prepared on a commercial electrolytic coating line at Double Eagle Steel Coating Company (Dearborn, MI) (Table 2). These coatings had roughly the same coating weight and were plated on different coils of DQSK sheet steels of similar mechanical properties and thickness (0.034 in.). The material coated on the commercial line is referred to as plant-coated steel. These lab and plant coating compositions allowed us to study the effect of iron concentration on friction characteristics for a range of concentrations centered at 12% Fe, which is the typical iron concentration of commercial products.

3. Test Approaches

A systematic study using the uniaxial tension test, bending under tension (BUT) test (90° bend) (Ref 9), drawbead simulation (DBS) test (Ref 10), limiting dome height (LDH) test (Ref 11), and deep-draw cup test (Fig. 2) was undertaken to evaluate various aspects of formability. The tension test was frictionless and was conducted to reveal the effect of coating on tensile properties such as work-hardening exponent and normal anisotropy. The BUT test was used to obtain coefficient of friction and represents friction of sheet steel over die radius. The DBS test was conducted to simulate the friction of sheet metal at a drawbead often used in sheet metal forming. A steel strip undergoes one bending and unbending process during a BUT test, but is subjected to a series of bending and unbending deformations in DBS. Since the die radius used in BUT was larger (0.375 in.) than those in DBS (0.187 in. for the male die and 0.06 in. at corner of the female die), the BUT test imposed mild surface contact and the DBS test imposed severe surface contact between the steels and the dies.

Forming behavior and coating friction under stretching were simulated in the LDH test using a 4 in. diam punch. The samples used in the LDH tests were panels of 7 in. length by variable width. Forming behavior and coating friction under deep drawing were simulated in the draw cup test on an Olsen tester. All the blanks used in the draw cup tests had the same diameter of 76 mm, and various blankholder forces were applied. Both friction and formability tests were performed on the lab-coated steels. Only friction tests were performed on the plant-coated steels because small differences in substrate properties may complicate interpretation of formability test results.

The lab-coated samples had single-side coatings for the BUT and LDH tests, and double-side coatings for the DBS and draw cup tests. The plant-coated materials had double-side coatings. An oil-base lubricant was used for the friction and formability tests. The amount of lubricant was kept roughly constant from sample to sample by allowing excess lubricant to drip off within 5 min.

4. Results of Simulative Formability Tests

The draw cup tests showed iron concentration in the coating to significantly affect drawability (Fig. 3). Blankholder force was varied so that a maximum cup height without wrinkling or breaking was obtained at each force. Wrinkling occurred before a full cup could be formed in the low blankholder force region. On the other hand, breaking occurred before a full cup could be formed in the high blankholder force region.

Results of the draw cup tests can be summarized as follows: (1) The maximum cup heights (punch depth) without wrinkling or breaking for 12.5 and 18% Fe samples were much higher than for 8% Fe samples; (2) 12.5 and 18% Fe samples had similar drawability; (3) the optimum blankholder forces for 8% Fe samples were much lower than those for 12.5 and 18% Fe samples; and (4) forming windows for 12.5 and 18% Fe samples were much larger than for 8% Fe samples. Full cups could be drawn without wrinkling or breaking over a wide range of blankholder force for 12.5 and 18% Fe samples, but no full cup could be drawn without wrinkling or breaking at any blankholder force for 8% Fe samples. Increasing coating weight reduced drawability slightly, as suggested by results for the 12.5% Fe samples.

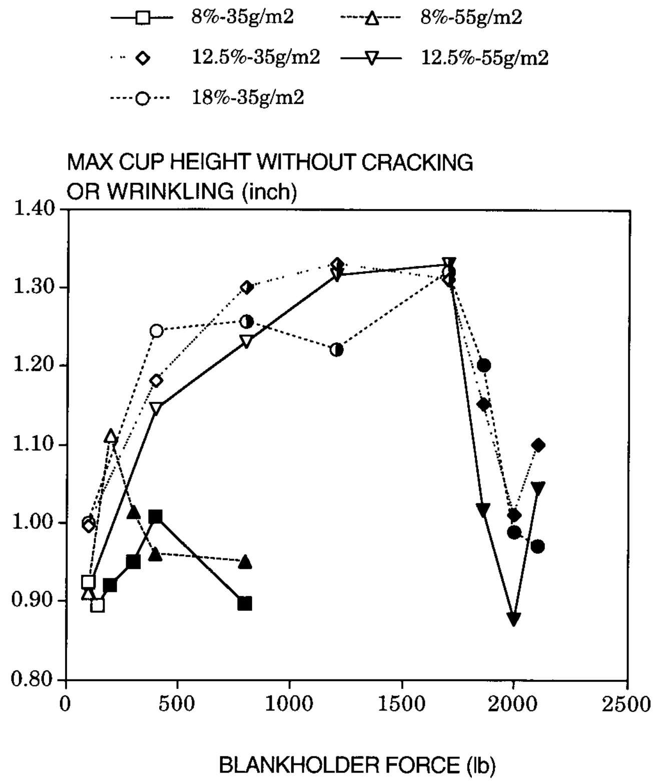


Fig. 3 Results of draw cup tests on lab-coated steels showing cup heights drawn before onset of wrinkling or breaking. The open and filled symbols represent occurrence of wrinkling and breaking, respectively, before a full cup was drawn. The half-filled symbols represent full cups without either wrinkling or breaking. Punch speed, 6 in./min

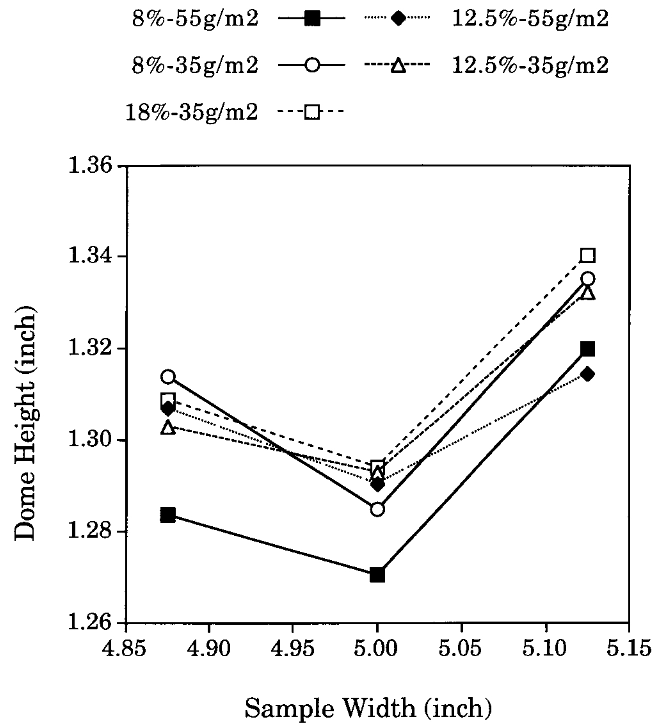


Fig. 4 LDH results for lab-coated steels

In contrast to the strong effect of coating in the draw cup test, coating played only a small role in the LDH stretching tests. All samples exhibited essentially the same dome height, with the exception of a slightly lower dome height for the 8% Fe, 55 g/m^2 sample (Fig. 4). The standard deviation of the LDH tests was between 0.005 and 0.01 in.

5. Results of Friction Tests

Test results on the lab-coated steels showed that coefficient of friction remains constant for coating compositions between 12.5 and 18% Fe and appears to become slightly higher at 8% Fe (Table 3). Friction tests on the plant-coated steel indicated that coefficient of friction also remains constant for coating compositions between 12 and 18% Fe (Table 4). The DBS allows more intimate contact between the die and the steel surfaces (Fig. 5). Only fixed beads were used in the DBS tests. Since the lab-coated steels had identical substrates, coefficient of friction was proportional to pulling force. The DBS showed a slightly higher frictional force for 8% Fe coating than for the other two coatings, which is consistent with the BUT results (Fig. 6). Even though the difference in coefficient of friction between samples is comparable to the standard deviation, the difference is likely real rather than statistical variation, because

Table 4 Coefficient of friction for plant-coated steels

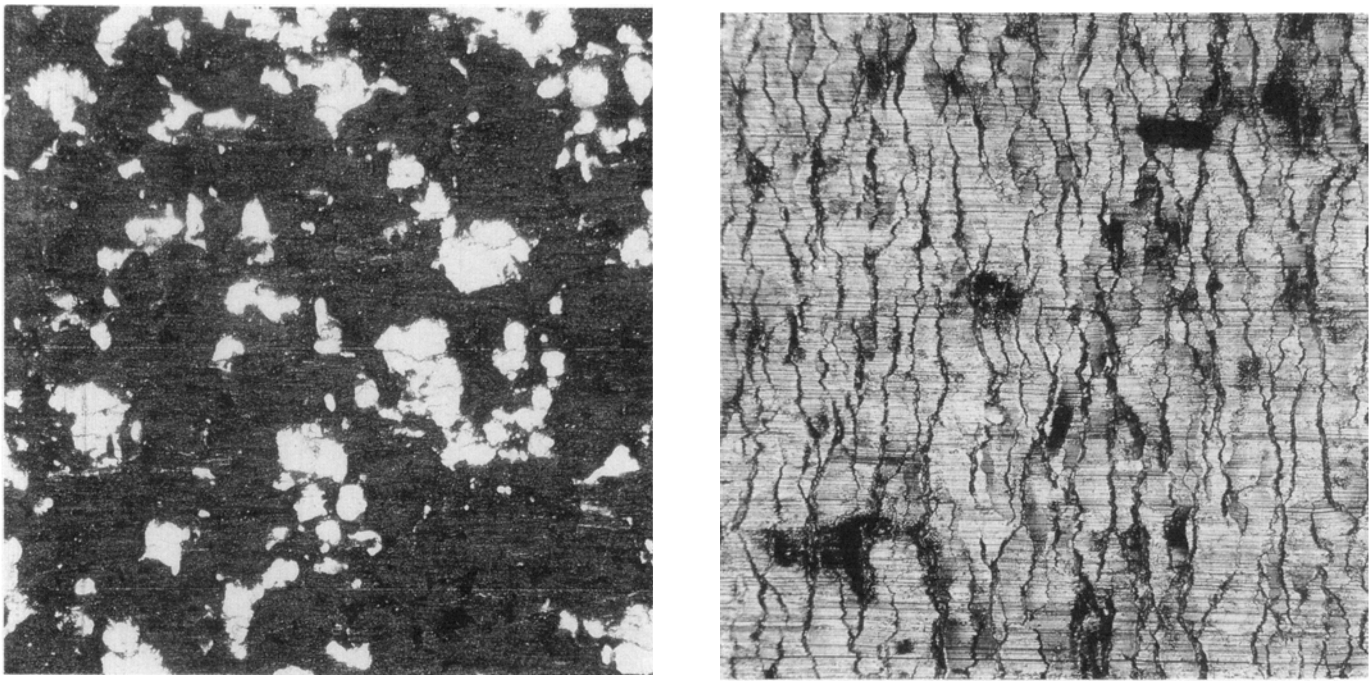
Coating weight, g/m^2	Coefficient of friction 12% Fe	14% Fe	18% Fe
50	0.14	0.14	0.14

Note: Standard deviation = 0.01; pulling speed, 10 in./min; die radius, 0.375 in.

BUT and DBS results are consistent with each other. Variation of coating weight does not seem to affect friction significantly.

6. Results of Uniaxial Tension Tests

Tension tests on the substrates of lab-coated steels confirmed the mechanical properties of the substrate used for various coatings to be the same. The coating reduced n-value and r-value, but had no significant effect on yield strength. The property most influenced by the coating appeared to be the r-value. Results similar to these findings have been reported for galvannealed steels and zinc-iron-coated steels (Ref 6, 8). The n-values were measured in 2 to 8% and 10 to 20% strain ranges. The effect of coating composition on the n-value is significant only in the higher strain range (Fig. 7). Figures 7 and 8 show that n-value and r-value are reduced by increasing iron concentration from 8 to 12.5%. However, the iron concentration has a smaller effect on n-values and r-values for coatings that contain more than 12.5% Fe, which is consistent with the result in Ref 7. The n-values and r-values decrease with increased coating weight (Fig. 9 and 10).



(a) (b)

Fig. 5 Contact areas (bright areas), showing that contact between the sample surface and the die is much more severe in DBS (b) than in BUT (a). 100×

Table 5 Fraction of contact in various tests

Coating	Fraction of contact, % BUT(a)	DBS(b)	LDH(c)	Draw cup(d)
8% Fe, 35 g/m^2	21.9	74.1	16.8	60.6
12.5% Fe, 35 g/m^2	15.8	70.4	12.8	46.5
18% Fe, 35 g/m^2	13.8	67.5	13.1	52.4
8% Fe, 55 g/m^2	20	76.8	16.0	N/A
12.5% Fe, 55 g/m^2	13.9	61.8	13.8	N/A

(a) At contact pressure of 1370 psi. (b) At clamping force of 2200 lb. (c) At half dome height. (d) At a location on cup wall equivalent for all samples

Table 6 Surface topography and topography change after BUT tests

Parameter(a)	8% Fe, 35 g/m^2	12.5% Fe, 35 g/m^2	18% Fe, 35 g/m^2
R_a, μin.	27.0	30.1	28.6
ΔR_a, %	−28	−19	−13

(a) R_a was measured transverse to the pulling direction. Δ represents change from the untested surfaces

7. Surface Characteristics and Discussion

In general, the experimental results showed correlation between formability and coefficient of friction; that is, lower coefficient of friction corresponds to higher formability, especially in draw cup tests. The effect of iron concentration on friction overwhelmed the effect of iron concentration on r-value, because the latter points to an opposite direction of the results of the draw cup tests. However, the decrease of r-value due to increased coating weight appears to have a small effect on drawability, as indicated by the slightly lower cup heights for the heavier coating of the 12.5% Fe sample. Since only the heavier 8% Fe coating showed lower dome height in LDH tests, it is not certain whether friction is the main factor. A lower n-value from the heavier coating may also have contributed to the lower dome height.

The following discussion deals with how friction was affected by coating composition, and why the difference in formability among coatings became much more significant in the deep-draw test. Table 5 shows that for all tests with tool-sheet contact, the fraction of contact for the 8% Fe coating was higher than for the 12.5 and 18% Fe coatings. The higher fraction of contact on the 8% Fe coating resulted from greater asperity flattening, as indicated by much greater change of surface roughness for 8% Fe in Table 6. Surface roughness of the 8% Fe coating becomes smaller than the 12.5 and 18% Fe coatings, although the initial surface roughness of the former was slightly higher. Knoop microhardness tests using a variable load on coating surfaces revealed the hardnesses of 12.5 and 18% Fe coatings to be higher than that of the 8% Fe coating (Fig. 11).

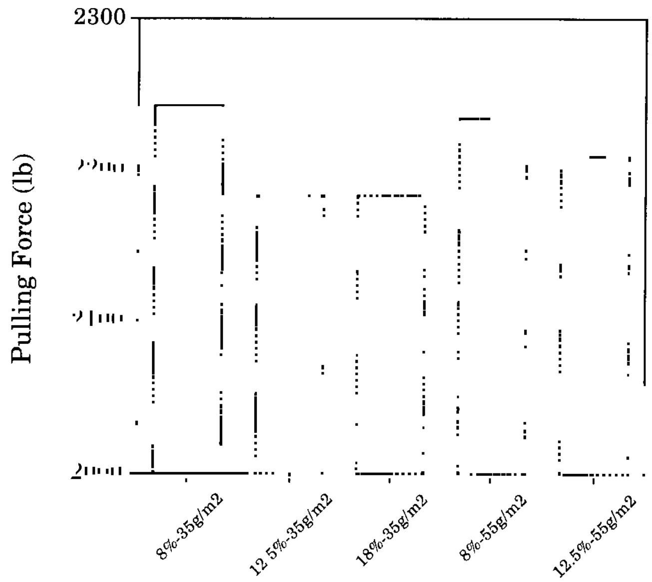


Fig. 6 DBS results for lab-coated steels. Pulling speed, 5 in./min; clamping force, 2200 lb

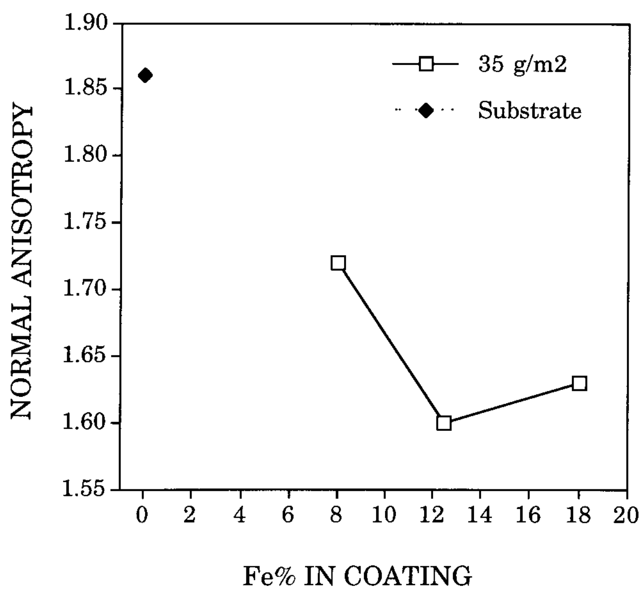


Fig. 8 Effect of iron concentration in the coating on *r*-value

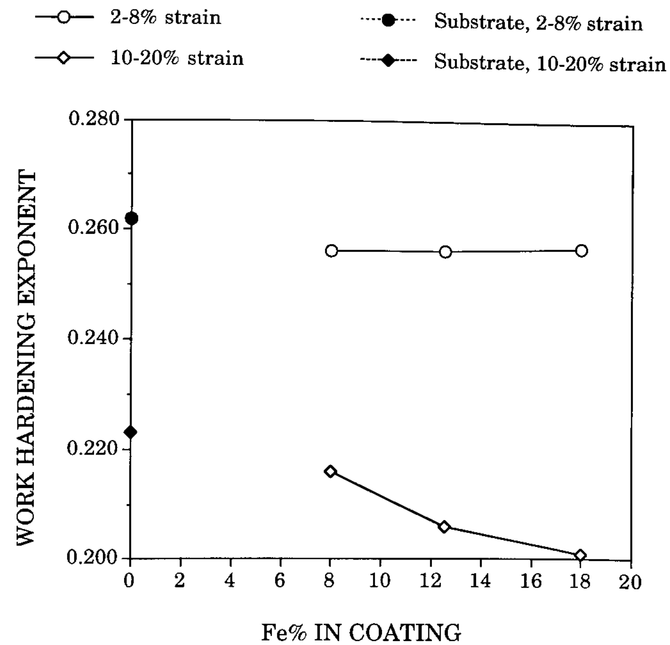


Fig. 7 *n*-value decreases with increasing iron concentration only at high strains.

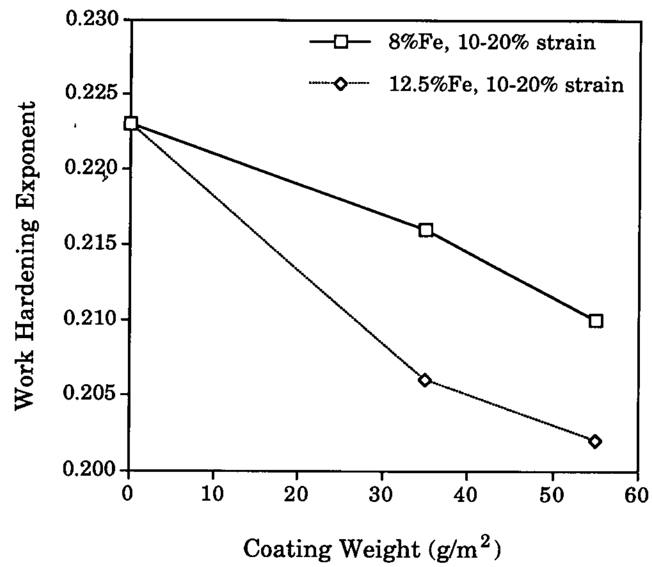


Fig. 9 *n*-value decreases with increasing coating weight

As the load was increased to 150 g, the hardness values for all coatings converged to about the same value because the indent was so deep that the hardness of the steel substrate was dominant. The difference in coating hardness among the samples was best represented by the test results at 50 g.

Therefore, as a result of the lower hardness of the 8% Fe coating, asperity flattening was much greater for 8% Fe coating than for 12.5 and 18% Fe coatings. Coating grains of the 8% Fe samples were smeared more severely than those of 12.5 and 18% Fe samples in the BUT and DBS tests, as shown in Fig. 12. More die marks were imprinted on surfaces of the lower iron concentrations during friction and formability tests, indicating more plowing and probably thinner lubricant (Fig. 12 and 13). Thus, coating composition affected coefficient of friction through contact area and contact conformity as a result of coating hardness variation.

It can be concluded that the lower formability of the 8% Fe samples was due to their higher coefficient of friction associated with the softer coating since substrate formability was same for all coatings. Since the hardness of 12.5% Fe coating is similar to that of 18% Fe coating, iron concentration variation in this range had a much smaller effect on *n*-value, *r*-value, friction, and formability tests. Since the differences in surface topography among the coatings were small, fraction of contact was governed mainly by the coating hardness associated with iron concentrations.

The next question, then, concerns why the effect of iron concentration was drastic in the draw cup test but not in the LDH and friction tests. Dependence of friction characteristics on deformation mode has been observed for other types of coated steels (Ref 6, 8). No satisfactory understanding of this phenomenon is apparent at this time. First of all, the fraction of contact in the draw cup test is much greater than in the BUT and LDH tests. Another factor could be the reaction of coating to different deformation modes. During the punch stretching, there was no compressive stress in the area of sample-punch contact. All the coatings accommodated the stretching similarly by cracks approximately perpendicular to the main stretch direction (Fig. 14). During the deep drawing, compressive stress occurred along the circumferential direction in flange area.

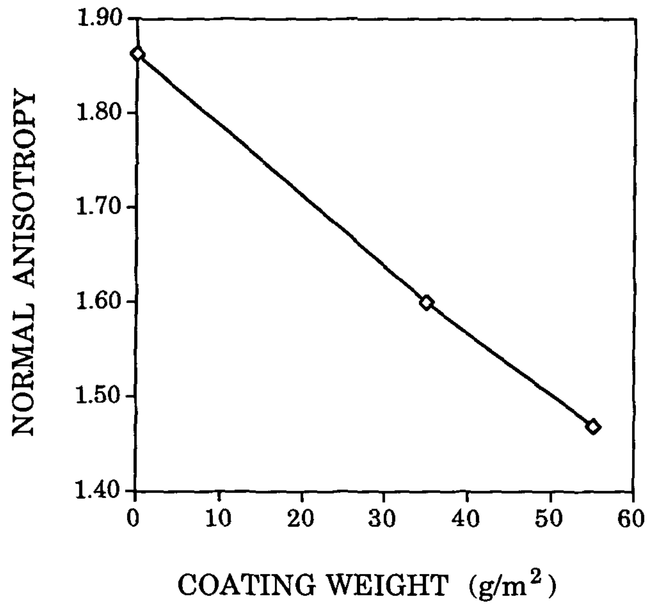


Fig. 10 *r*-value decreases with increasing coating weight. 12.5% Fe

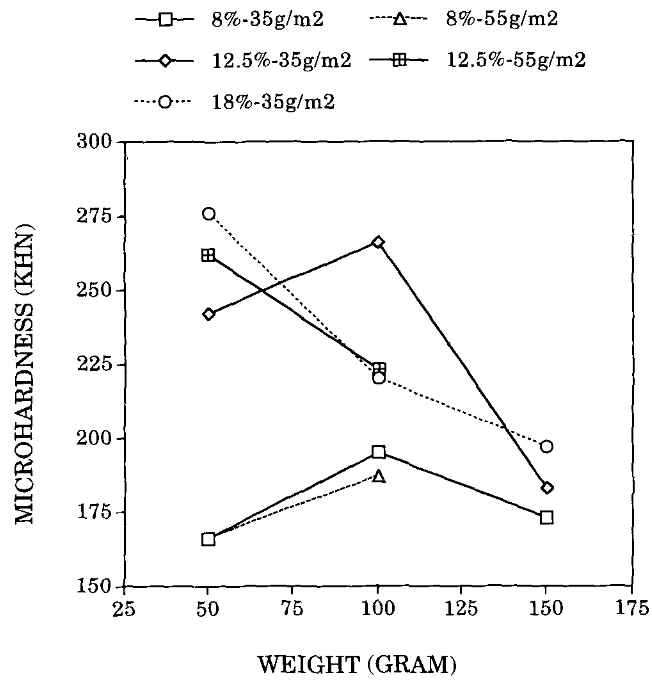
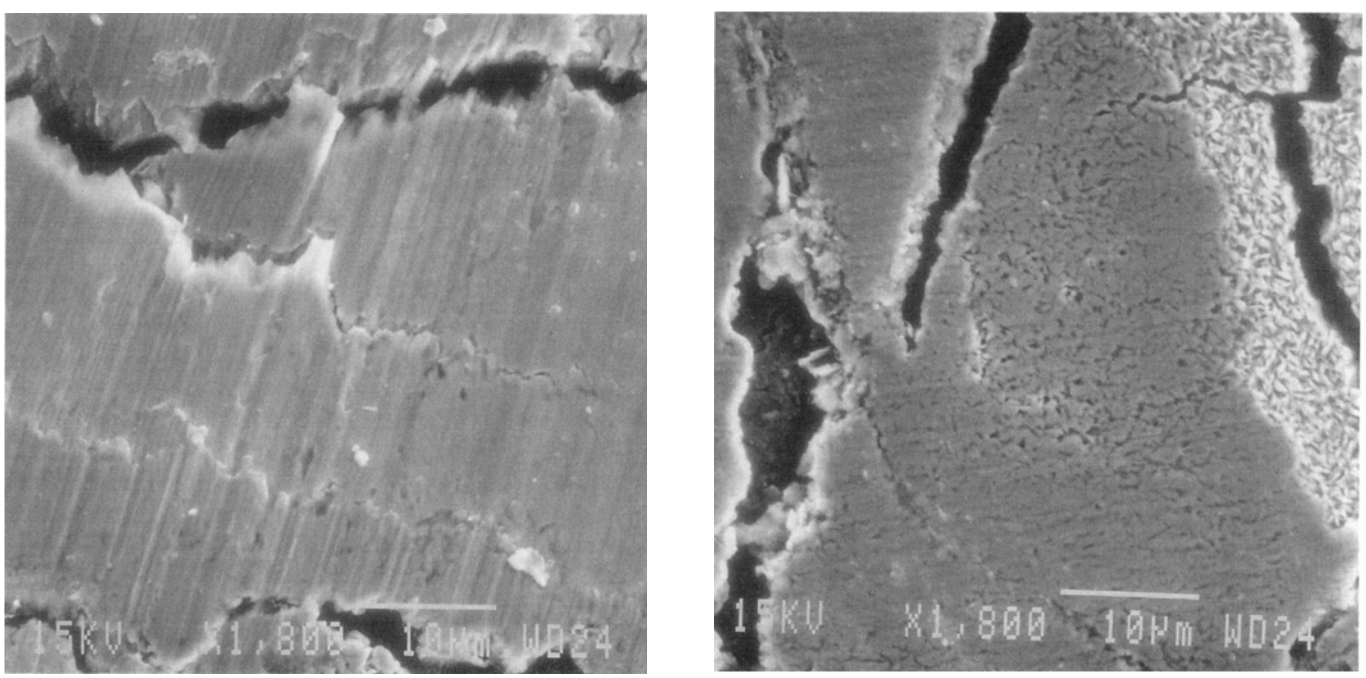
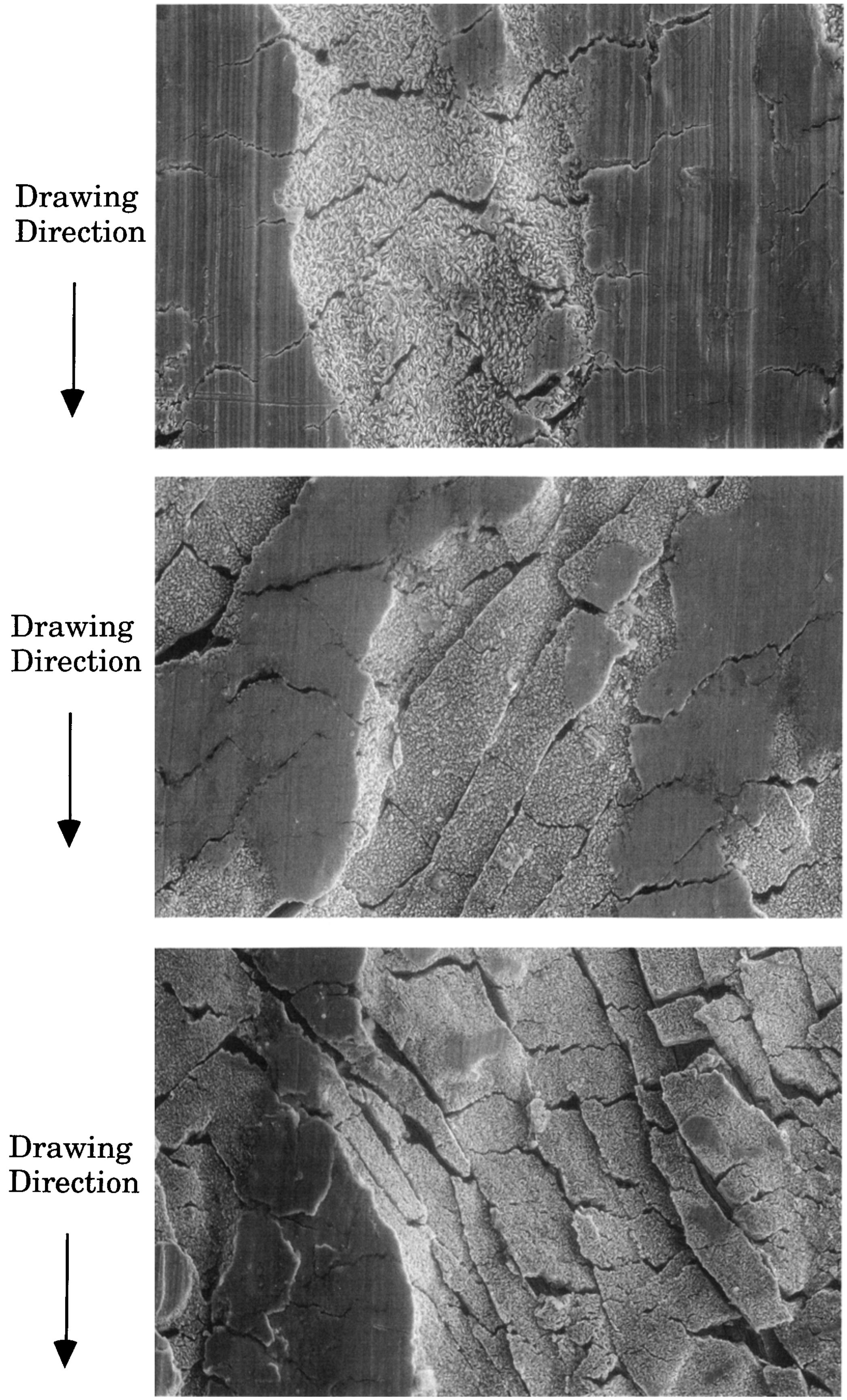


Fig. 11 Knoop microhardness of the coatings at different iron concentrations. The indents were made on the coating surfaces.



(a) (b)

Fig. 12 Asperity flattening of the lab-coated steels in DBS tests. 1800×. (a) 8% Fe, 35 g/m^2. Coating crystals were completely smeared in most contact areas. (b) 18% Fe, 35 g/m^2. Coating crystals were not completely smeared in most contact areas.

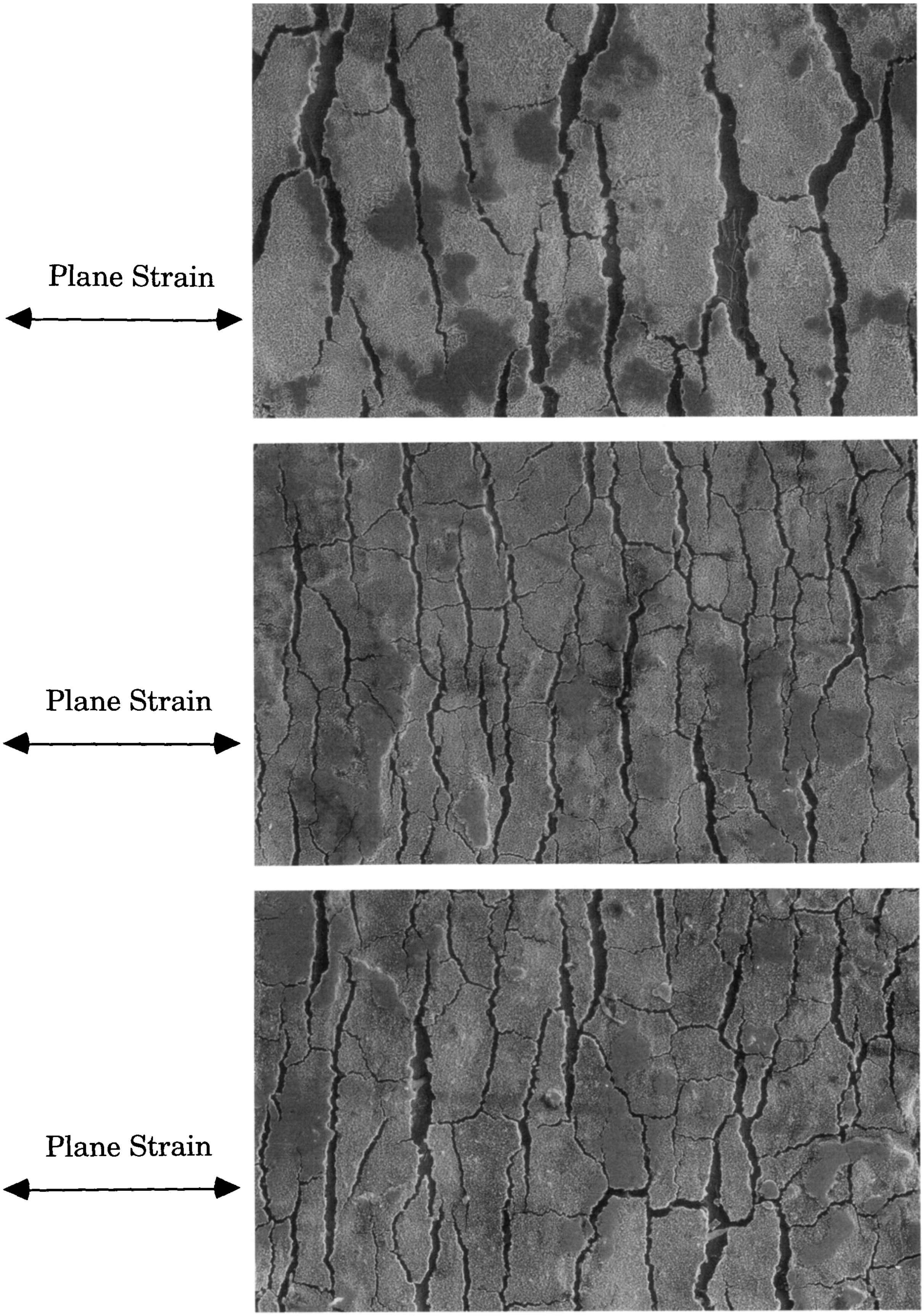


(a)

(b)

(c)

Fig. 13 Surface morphology of the draw cup walls, showing difference in severity of die marks and crack pattern between 8% Fe coating and the other two coatings. 700×. (a) 8%, 35 g/m^2. (b) 12.5% Fe, 35 g/m^2. (c) 18% Fe, 35 g/m^2



(a)

(b)

(c)

Fig. 14 Surface morphology of the LDH samples near plane strain, showing similarity in crack pattern between 8% Fe coating and the other two coatings. 350×. (a) 8%, 35 g/m^2. (b) 12.5% Fe, 35 g/m^2. (c) 18% Fe, 35 g/m^2

Figure 13 shows that the 8% Fe coating reacted to the drawing operation differently from the 12.5 and 18% Fe coatings. Two sets of cracks are visible on the draw cup samples: One is approximately perpendicular to the drawing direction, the other inclined to the drawing direction. The first set of cracks prevailed in the 8% Fe coating, and the second set prevailed in the 12.5 and 18% Fe coatings. Because the 12.5 and 18% Fe coatings were more brittle than the 8% Fe coatings, they did not thicken as much. Instead, they accommodated compressive stress in the flange area by developing the second set of cracks and by small overlapping among cracked pieces of the coating in the noncontact areas (Fig. 13b and c). The overlapping was created by the compressive strain in the circumferential direction. The greater thickening in the 8% Fe coating under the compressive stress tended to increase contact pressure and thus frictional force. In contrast, the tendency of the contact pressure and the frictional force to increase in the 12.5 and 18% Fe coatings may have been greatly relieved by the second set of cracks and by the overlapping.

This study suggests that better formability can be obtained with iron coating concentrations of approximately 12% or greater. However, powdering may increase significantly as iron concentration rises above 18% (Ref 3, 5). Optimum cosmetic corrosion resistance is provided by coatings with iron concentrations in the range of 12 to 15% (Ref 2).

8. Conclusions

For coating iron concentrations between 12 and 18% Fe, variation of concentration had a negligible effect on coefficient of friction and formability. For coating iron concentrations below 12%, the coefficient of friction in the BUT test became slightly higher as the iron concentration was reduced to 8%. However, frictional force in formability tests depended strongly on the deformation mode in this composition range. Frictional force in the stretching operation may have increased slightly with decreasing iron concentration. In contrast, frictional force in the drawing operation increased tremendously with decreasing iron concentration, as indicated by the significantly lower drawability for the 8% Fe coating. The effect of coating weight on friction was not significant.

Increases in iron concentration and coating weight reduced both *n*-value and *r*-value. Drawability was reduced slightly as coating weight was increased from 35 to 55 g/m^2. The effect of iron concentration on *n*-value and *r*-value was overwhelmed by the effect of iron concentration on frictional force in the drawing operation. The effect of iron concentration on *n*-value and *r*-value becomes smaller in the range of 12 to 18% Fe.

The coating hardness altered by iron concentration dictates friction characteristics, *n*-value, and *r*-value. Lower coating hardness due to lower iron concentration results in a higher fraction of contact and contact conformity, which is associated with a higher frictional force.

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