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Research on the Metallurgical Determinants of Formability in Electrogalvanized Sheet

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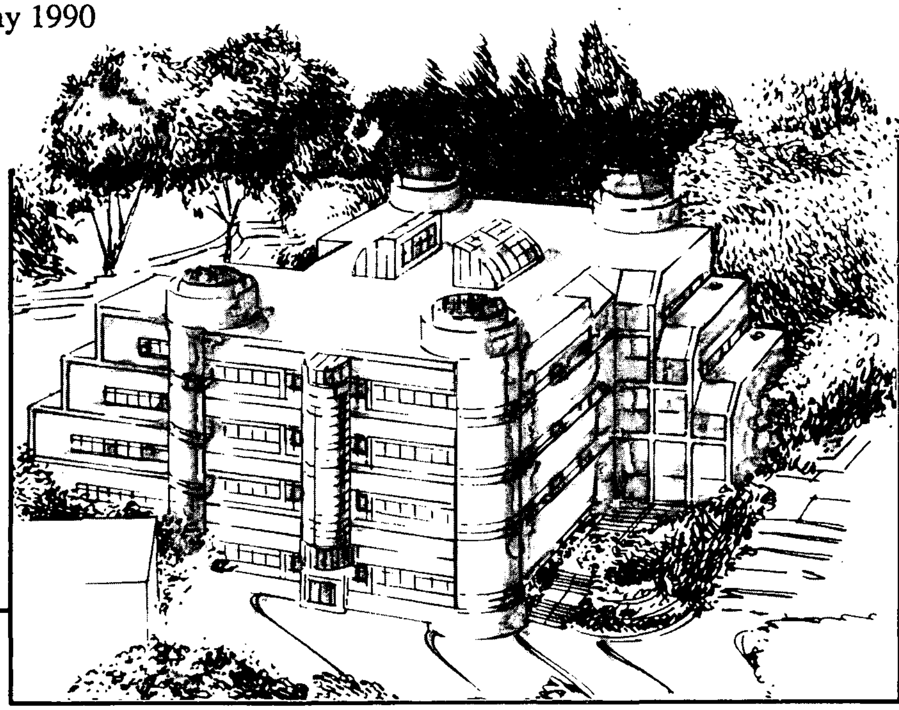
May 1990



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The effective coefficient of friction in draw-bead simulation tests of two-sided electrogalvanized steels (DBS-μ) varies significantly. Analysis of commercial samples suggests that the surface roughness and crystallographic texture of the coating are important variables. To isolate the effect of texture one-side galvanized samples of various textures were made in a laboratory simulator and tested in draw-bead simulation and strip-draw. The data show a consistent variation of DBS-μ with texture. Differences between the DBS and strip-draw tests apparently reflect differences in the degree of deformation on initial contact with the bead. The DBS-μ also increases when the surface is smooth on the microscale, probably because of interaction with the lubricant. However, the results do not seem to explain the quantitative differences between commercial specimens, which suggests that other metallurgical factors, such as surface roughness and the properties of the underlying steel, and often dominate.

I. Introduction

Two-side electrogalvanized steel is increasingly used in vehicle body panels to improve corrosion resistance. While many types of galvanized coating have been developed by steel suppliers, the domestic automobile industry has preferred electrodeposited coatings of pure zinc, and will likely continue to do so[1]. The electrogalvanized layer is a source of difficulty in vehicle manufacture since it changes the forming, welding and painting characteristics of the sheet. Two forming problems are of particular concern[2]. First, the zinc galvanized layer significantly increases the effective friction between the steel and the workpiece during forming. Second, and often more important in the practical sense, the effective friction varies significantly from one manufacturer to another and even from lot to lot. To optimize the use of electrogalvanized steel in vehicle manufacture it is necessary to understand the metallurgical sources of friction during forming to permit the manufacture of reproducibly formable steel and to provide reliable inspection and quality control procedures.

Understanding friction during the forming of galvanized steel is made difficult by the complexity of the coated layer and the forming process. The surface of the coated steel is a composite of an underlying steel sheet, a thin zinc coating, and a (usually) liquid lubricant. The morphology and the mechanical properties of each element of the composite affects the interaction between the sheet and the forming tool. The interaction also depends on the geometry of the tool and the nominal loads that are applied.

To conduct fundamental research into the sources of friction one must define a laboratory test or set of tests that simulate the behavior of coated steel during forming, identify and characterize the pertinent metallurgical characteristics of electrogalvanized steel, and develop specific tests and sample preparation procedures that isolate the important variables. For the research reported here the draw-bead simulation (DBS) test[3] was used to measure effective friction, since it is the formability test that is most widely accepted in the automotive industry[4]. A variety of commercial steels were tested and studied to gain some insight into the variables that determine the effective friction. The results indicate that the crystallographic texture of the zinc layer may be an important parameter. In an attempt to isolate this variable, coatings with a variety of textures were electrodeposited in a laboratory facility at LTV steel, tested and analyzed. The results of these experiments show two separate effects that are associated with the change in texture: it alters the mechanical properties of the layer and establishes a pattern of microroughness on the surface that apparently affects the behavior of the lubricant. However, the results also suggest that the texture is often quantitatively subordinate to other factors in determining the effective friction of commercial electrogalvanized steels in the draw-bead simulation test.

II. Analysis of Commercial Zn Coatings

Samples of two-side electrogalvanized steel from a variety of manufacturers were procured and tested in collaboration with the Ford Motor Company. Nineteen separate samples were tested. The DBS-μ values varied from 0.097 to 0.27, and were distributed rather uniformly over that range. The results also showed significant variations among specimens from individual manufacturers.

The crystallographic textures of the Zn coatings and the roughness of the coating surfaces was studied. While there were also differences in underlying steels, these were not characterized in this particular set of experiments. The lubricant was not a variable since the same lubricant (mill oil) was used in all tests.

To understand the role of the roughness it is useful to divide it into three size regimes: *waviness*, which includes deviations from flatness that are large compared to the local dimensions of the tool-piece, *macroroughness*, which includes surface asperities whose dimension is less that that of the tool but large compared to the thickness of the coating ($\approx$ 10 μm), and *microroughness*, which includes irregularities that are small compared to the layer thickness. As illustrated by the example shown in Fig. 1, in the usual case the macroroughness is dictated by the underlying steel sheet; a typical electrogalvanized zinc layer coats the surface uniformly. The microroughness, on the other hand, is set by the coating itself. Examples of microroughness on the commercial specimens are given in Fig. 2. The macroroughness is the dominant parameter that governs the interaction between the sheet and the toolpiece. The tool contacts the sheet at high points in the macroroughness profile. The result is illustrated in Fig. 3, which shows the deformation pattern on an electrogalvanized sample after testing in a draw-bead simulator. The surface is deformed in discrete areas that correspond to high points on the original surface. The microroughness does not directly affect contact with the toolpiece (though it has an indirect effect that we shall discuss later). As shown in Fig. 3, microroughness is obliterated wherever the surface is deformed, and is undistorted in the intervening areas.

The crystallographic texture of the coatings was measured by x-ray diffraction using techniques that are described in ref. [5]. The textures of the specimens can be divided into four prototypic types, based on the predominant crystallographic plane parallel to the plane of the coating. The prototype textures are illustrated in Fig. 4; the examples in the figure are taken from laboratory specimens. They are termed: (1) *basal*, in which the $\{0001\}$ basal planes of the hexagonal Zn crystal lie in the coating plane, (2) *low-angle pyramid*, in which the $\{10\bar{1}4\}$ or $\{10\bar{1}3\}$ planes parallel the coating, (3) *high-angle pyramid*, in which $\{11\bar{2}2\}$ planes parallel the coating, and (4) *prismatic*, in which the prismatic $\{11\bar{2}0\}$ planes predominate in the coating plane. The texture is most simply represented by bar-graphs, shown in the figure, that plot the relative fractions of the various crystallographic planes in the plane of the sheet; pole figures and orientation distribution functions can be used for more precise characterization[5]. The crystallographic texture correlates to the microroughness, as indicated by the examples in the figure.

Equipment limitations prevented a systematic, quantitative study of macroroughness at the time this research was done. However, we did observe a correlation between the coating texture and the coefficient of friction in the draw-bead simulation tests (DBS-μ). The coefficient of friction tended to decrease as the predominant texture rotated from basal to pyramidal to prismatic. Some of the results are presented in Fig. 5, which compares the textures of a sample with high DBS-μ and significant basal texture to that of a sample with low DBS-μ and nearly prismatic texture. A second effect of the texture was an increased tendency toward micro-fracture in the coating as the grain orientation became more nearly prismatic. The extensive surface cracking in a sample with prismatic orientation is shown in Fig. 6.

The correlations noted here were not universal. Some of the samples with low DBS-μ had pyramidal textures, there was substantial scatter in friction coefficient among samples with similar texture, and microcracking was observed in samples with non-prismatic orientations. However, the correlation between texture and DBS-μ was sufficiently strong to warrant further investigation. For that reason we joined with LTV Steel to create a set of samples with varied coating texture on a given substrate steel, in an attempt to isolate the influence of texture on the DBS-μ.

III. Research on Laboratory Samples

To produce samples that isolate texture as a variable, a set of 64 nominally identical AKDQ steel strips were electrogalvanized on one side in a rotating cathode electrogalvanizing facility in the research laboratories of LTV Steel. The samples were 6"x20" (15x50 cm.) blanks of sheet 0.029" (0.1 cm.) in thickness, with the long axis in the rolling direction. They were formed into 6" (15 cm.) diameter cylinders for electrodeposition from a 6"x1" (15x2.5 cm.) insoluble anode. Coatings of ≈10 μm thickness (corresponding to G70 coatings) were plated under a variety of conditions to vary sample texture. Five duplicate sheets were coated in each condition. Of the 64 pure Zn specimens, 31 had strong basal texture, 12 low-angle pyramid, and 8 high-angle pyramid. The remainder were mixed in texture. No strong prismatic textures appeared.

In an attempt to obtain prismatic texture and vary the properties of the coating, 10 additional specimens were deposited from baths doped with 50-500 ppm Cd, Sn and Ni. The Cd addition was successful in creating a prismatic coating. The predominant texture rotated monotonically toward prismatic as the Cd content of the bath was increased, as shown in Fig. 7, and a strongly prismatic texture was obtained with a 500 ppm Cd addition. It is not yet clear how much Cd is incorporated into the coating, or in what form; the microhardness of the deposited layer increased on Cd addition, but the hardness of the 10 μm film is difficult to measure precisely, and the results of hardness measurements scattered too widely for quantitative conclusions to be drawn.

The simulated coatings were large-grained, compared to the commercial ones, and it was possible to study their microstructures in cross-section. Etched metallographic cross-sections of two different coatings are shown in Fig. 8. These show that the grain structure is sometimes columnar single-grained, and sometimes polygranular through the coating. Fine-grained, columnar and coarse-grained, polygranular coatings had somewhat different frictional properties when the crystallographic texture was basal, and we hence distinguish the two cases in the following.

The microroughnesses of the coatings are shown as a function of texture in Fig. 4. The surface of the prismatic, Cd-doped coating is particularly interesting. A detail of the surface and a cryofractured cross-section are shown in the upper two micrographs in Fig. 9. The surface is dotted with rounded hillocks with dimensions on the order of the coating thickness. The hillocks contribute to the macroroughness of the coating, and directly influence its response to the die, as illustrated by the lower micrograph in Fig. 9. These coatings are an exception to the general rule that the macroroughness is fixed by the surface of the underlying steel (other exceptions are discussed in ref. [6]).

Up to 12 test strips, 6"x1.5" (15x3.8 cm.), were cut from each coated sheet for friction testing at Ford Motor Company. Leaders were welded onto one end of the strips to provide the 14" (35 cm.) total length needed for the tests. Two types of tests were done: draw-bead simulation tests and strip draw tests that measure surface friction without bending the sample. The samples were lubricated prior to testing by brushing on mill oil to achieve a saturated lubrication condition. Both tests were done in stroke control at 200 in./min. (500 cm./min) pulling speed.

The draw-bead simulation tests used the procedures outlined in ref. [3], with one exception. Since preliminary experiments showed that the results depend strongly on coating orientation when only one side is electrogalvanized, the tests were done with the zinc coating oriented toward the single bead, and with roller beads on the bare steel side to exclude any frictional contribution from the steel. The equation for calculating the coefficient of friction was modified accordingly. Four samples were tested with a fixed bead and two with a roller bead to determine an effective DBS-μ (termed OSDBS-μ). The strip-draw tests used a device in which a strip sample is clamped between a fixed bead and a roller bead and the pulling force measured as a function of the clamping force. Again, the tests were done with the coated side of the strip facing the fixed bead.

The results of the draw-bead simulation tests are summarized in Fig. 10. The friction coefficients are higher than those measured for the commercial specimens, but this is expected given the difference in test procedure. The results qualitatively reproduce the trends seen in the commercial specimens: the sample with the lowest effective friction had prismatic texture while the sample with the highest effective friction had a basal texture. However, there is a consistent difference between fine-grained and coarse-grained basal specimens; the fine-grained specimen had a relatively high coefficient of friction while the coarse-grained specimen did not. It must also be noted that the Cd-doped prismatic specimen was both harder and rougher than the undoped specimens.

The texture of the coating affects at least two different mechanistic variables that may influence the coefficient of friction: the plastic properties of the coated layer and the microroughness, which may affect the wetting and flow of the lubricant on the galvanized surface. Two additional sets of experiments were done in an attempt to separate these variables. First, chemical etchants were identified that largely erase the microroughness of the galvanized surface, and were used to compare the friction on surfaces that are nearly smooth on the microscale. Second, strip draw tests were performed to obtain data on the effective friction of the galvanized coating in the absence of deformation of the substrate.

To eliminate microroughness strips were cleaned in acetone and ethyl alcohol, then submerged for 15 seconds in a solution of 5% HNO_3 (70% concentrated) in distilled water. After etching the strips were dipped in distilled water, rinsed in ethyl alcohol and dried in hot air. The results of this treatment are shown in Fig. 11. The microroughness is largely removed. The macroroughness is not significantly affected by the etching treatment; the macroroughness due to the Zn hillocks on the prismatic specimen is also retained.

Fig. 12 shows the results of draw-bead simulation tests on the micro-smoothed surfaces. The effective coefficient of friction (OSDBS-μ) increased in every case by 10-15%, but the fractional increase was relatively insensitive to the texture. The results suggest that microroughness is important, probably because of its influence on the lubricant, but the detailed morphology of the microroughness is less important. In particular, removing the microroughness does not significantly change the relative friction of the various coating textures.

Fig. 13 presents results of the strip draw tests. The effective coefficient of friction (the pulling load divided by the normal load) is almost independent of the normal load. In agreement with the results of the DBS tests, the coefficient of friction is almost the same for the pyramidal and coarse-grained basal specimens, and is significantly lower for the prismatic, Cd-doped specimen. The difference between the two data sets concerns the fine-grained basal specimens, which had higher friction than the pyramidal specimens in the DBS tests, but an almost equal coefficient of friction in the strip draw tests.

This behavior can be interpreted in light of the data plotted in Fig. 14, which shows the area fraction deformed in the strip-draw tests as a function of the normal load for the different specimens. At normal loads in the range 100-300 lbs., which are typical of the draw-bead simulation test, the contact between the die and the coated surface deforms a significantly greater area fraction of the fine-grained basal specimen than the pyramidal specimens. The greater extent of the surface deformation does not lead to a higher coefficient of friction in the strip-draw test, which suggests that the fine-grained basal coatings were softer and required less plastic work per unit volume deformed. But the bead-surface contact in the strip-draw test is along a single band, while in the DBS test contact is maintained as the strip slides over the bead. If the increased area of contact raises the effective friction as the strip continues to slide over the bead in the DBS test, it is reasonable that the fine-grained basal specimen will exhibit a higher DBS-μ.

The more extensive deformation of the fine-grained basal coating relative to the coarse-grained basal coating was surprising, since fine grain size ordinarily increases hardness. This result is being investigated further. Note, however, that "fine-grained" in this context refers to the grain cross-section in the plane of the coating. The actual grain size depends on grain shape as well as cross-section. The grain shape may also influence the tendency toward twinning in preference to plastic deformation, which offers a relatively easy deformation mode[5]. A light galling was observed on the bead after the tests, which may also influence the result (as discussed for example, in ref. [7]).

The lower friction of the prismatic surface reflects four factors that are difficult to separate, all of which may contribute to the smaller deformed area in the strip-draw test. The Cd-doped surface is rougher on the macroscale, which minimizes the initial area of contact, it is harder because of the Cd addition, which minimizes deformation once contact is made, it may also be harder crystallographically[8], and it is prone to fracture, which places an upper limit on the extent of plastic deformation[5], lowering the plastic work done per unit area of contact.

IV. Conclusion

The results of tests on laboratory specimens show that the crystallographic texture of the coated layer does influence the effective friction in the draw-bead simulation test. The trend is that friction decreases in the textural sequence basal → pyramidal → prismatic. However, the trend is relatively weak except in the prismatic case, is not always observed (for example, basal texture yields high friction only when the coating is fine-grained), and is complicated by other effects, such as the coupling between texture and microroughness and solution hardening, which may have significantly affected the results for the prismatic specimen.

The results reveal significant differences between friction in draw-bead simulation and simple strip-draw tests in the particular case of the fine-grained basal specimens. A closer analysis of the surface deformation in the strip-draw test suggests a possible explanation: differences in the surface area deformed on contact between the bead and the sample surface may have a much larger effect in tests, like the DBS test, in which bead-to-sample contact is maintained through a significant sliding displacement. This analysis suggests one reason why the draw-bead simulation may provide a better correlation to performance during forming than simple friction tests.

However, the results of these tests show that even significant variations in crystallographic texture from the basal through the pyramidal orientations do not change the effective friction sufficiently to explain the large variations observed in commercial specimens. Other factors must play an important role. The obvious factors are the macroroughness of the surface and the properties of the underlying steel. The two may even be coupled. Tests done in this laboratory[5] in which coated steels are stretched in tension show changes in the macroroughness of the surface that are apparently due to surface roughening of the steel substrate.

Finally, the results of studies on artificially smoothed surfaces suggest that the microroughness of the electrogalvanized layer has an independent effect on friction that is probably associated with the behavior of the lubricant. This effect deserves further study.

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Figure Captions

Fig. 1: Cross-section of electrogalvanized steel.

Fig. 2: Examples of microroughness on four commercial electrogalvanized steels.

Fig. 3: Detail of the deformed surface of an electrogalvanized steel.

Fig. 4: Prototypic textures of electrogalvanized coatings, with associated microroughness patterns.

Fig. 5: Textures of two commercial specimens: the low-friction coating ($\mu = .106$) has a relatively prismatic texture while the high-friction coating [$\mu = .241$] has a relatively basal texture.

Fig. 6: Microcracking in the surface of a tested specimen with prismatic texture.

Fig. 7: Change in surface texture with Cd addition to the plating bath.

Fig. 8: Columnar and polygranular structures of the laboratory coatings.

Fig. 9: Micrographs of the coating deposited from a bath containing 500 ppm Cd; top: overview of surface; middle: cryofractured sample showing cross-section and surface roughness; bottom: cryofractured sample showing cross-section and coating after DBS testing.

Fig. 10: Average values of DBS-μ for one-side coated specimens (OSDBS-μ) as a function of texture.

Fig. 11: Micrographs showing smoothing of lightly etching surfaces with three microroughnesses.

Fig. 12: Change in OSDBS-μ when samples are smoothed by light etching.

Fig. 13: Results of strip-draw tests of the five specimen types (textures labelled as in Fig. 4).

Fig. 14: Area fraction deformed as a function of normal load in the tests shown in Fig. 13.

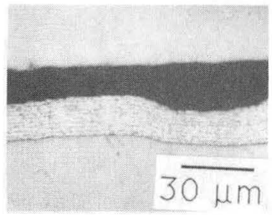

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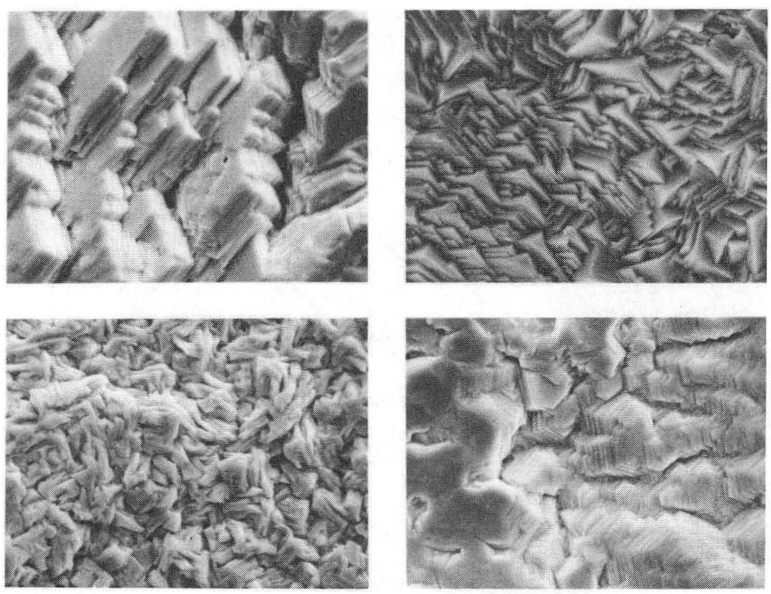
Figure 1



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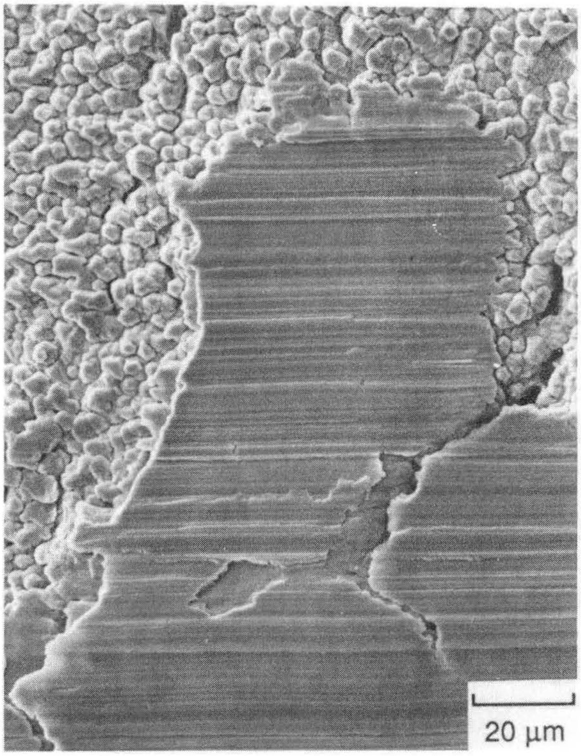

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Figure 3

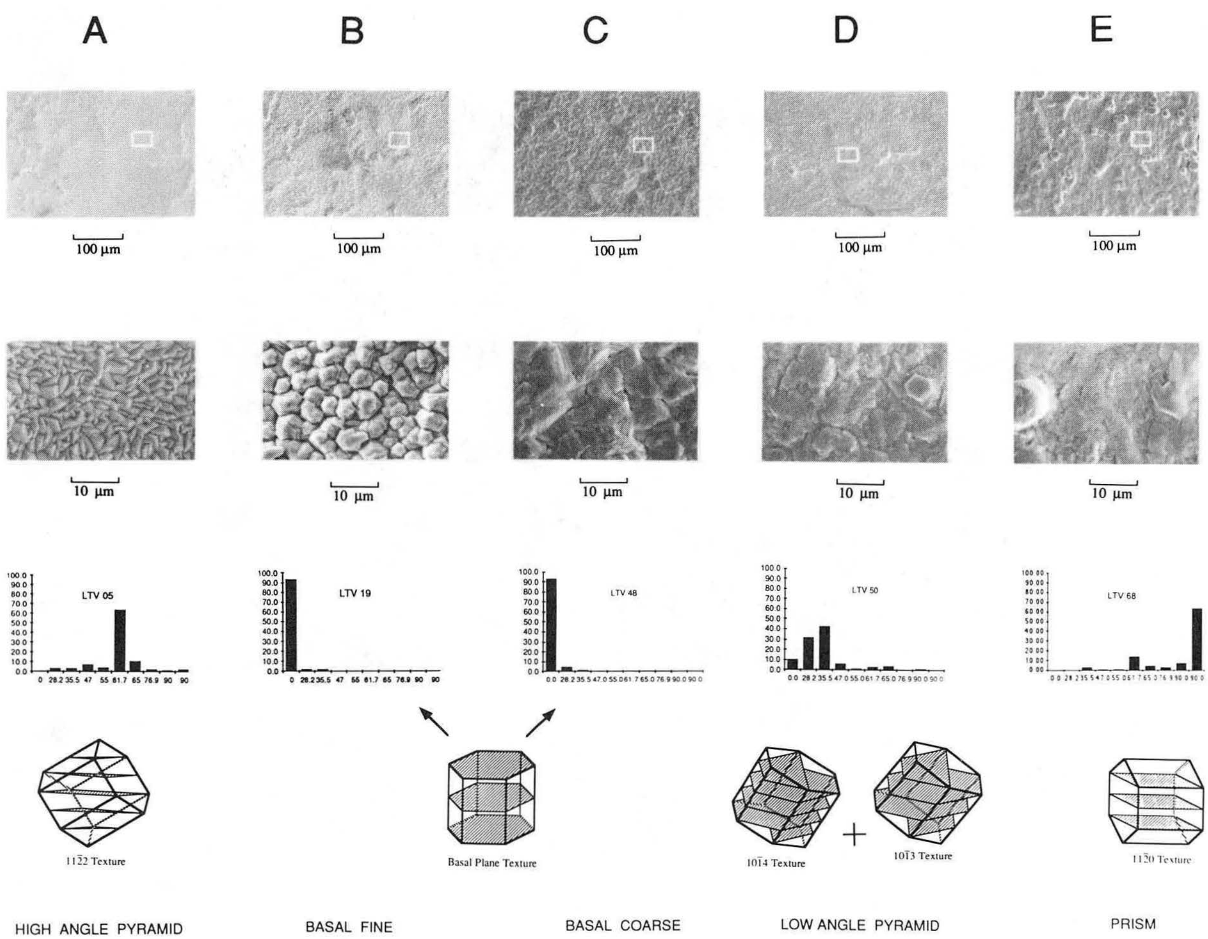

Figure 4

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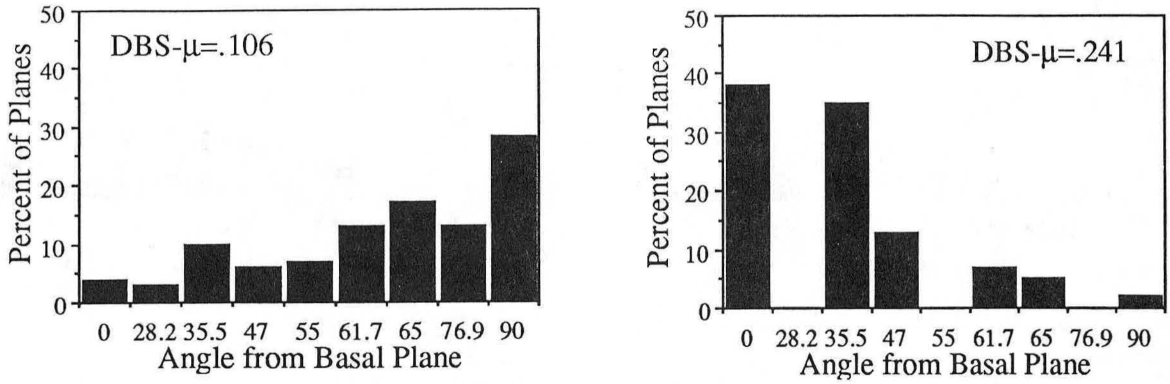

Figure 5

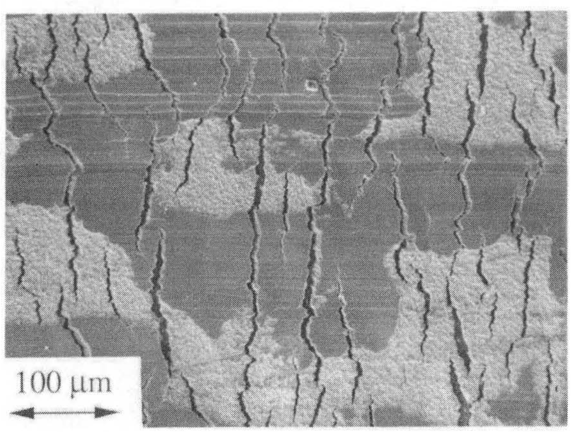

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Figure 6

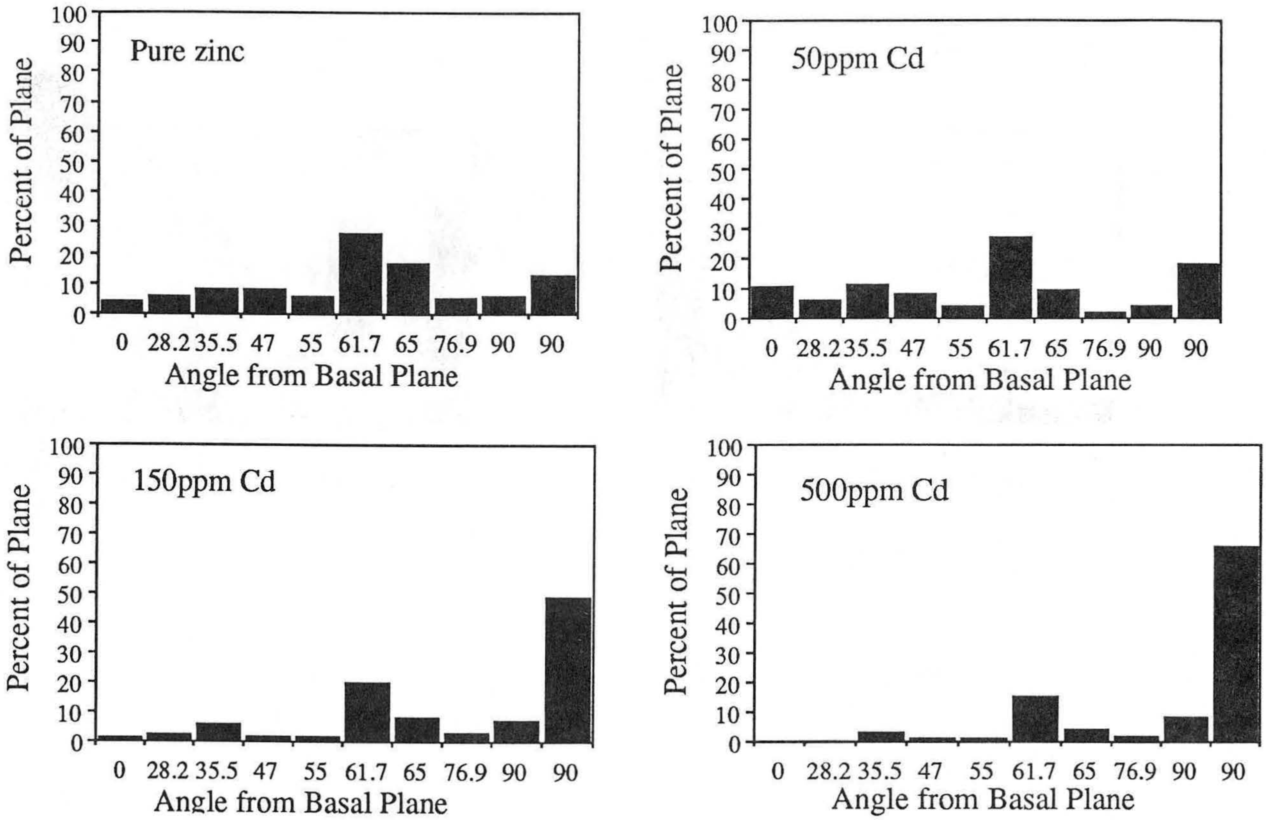

Figure 7

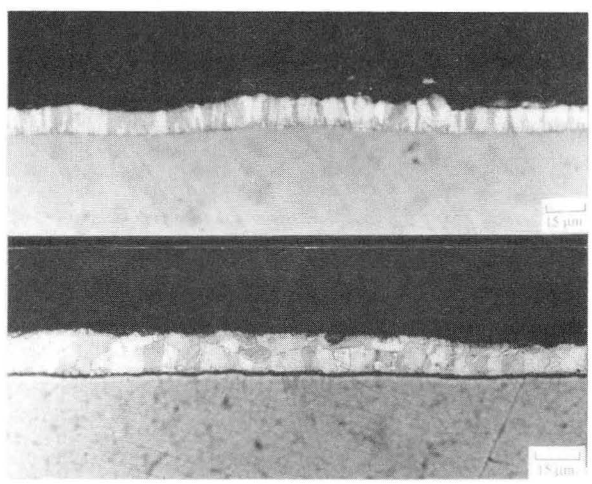

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Figure 8

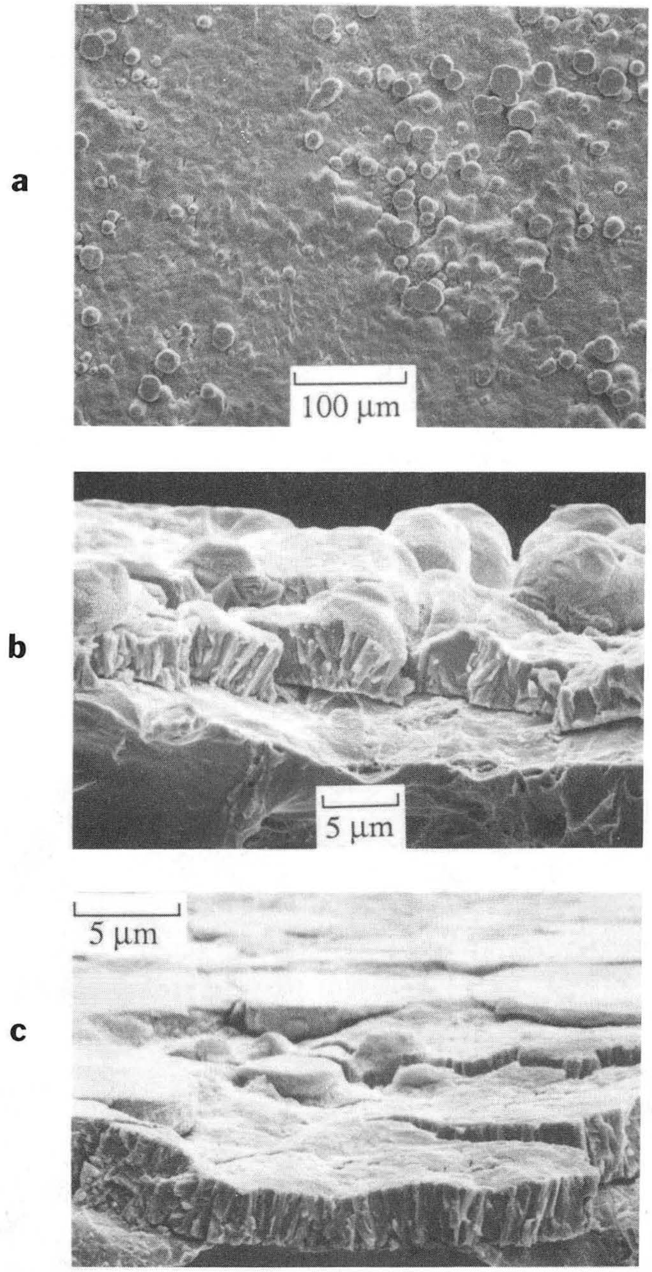

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Figure 9

COEFFICIENTS OF FRICTION FROM ONE-SIDED DBS TESTS

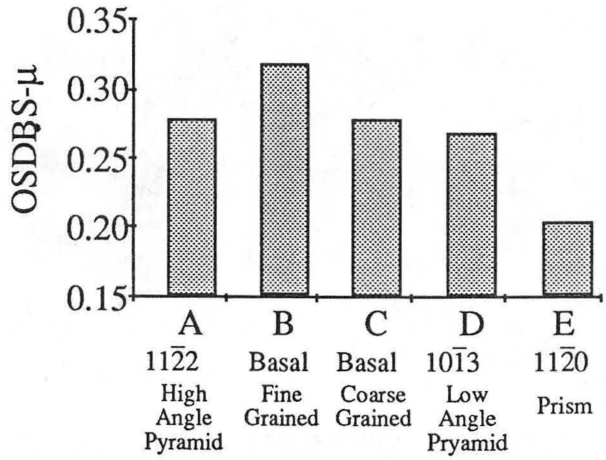

Figure 10

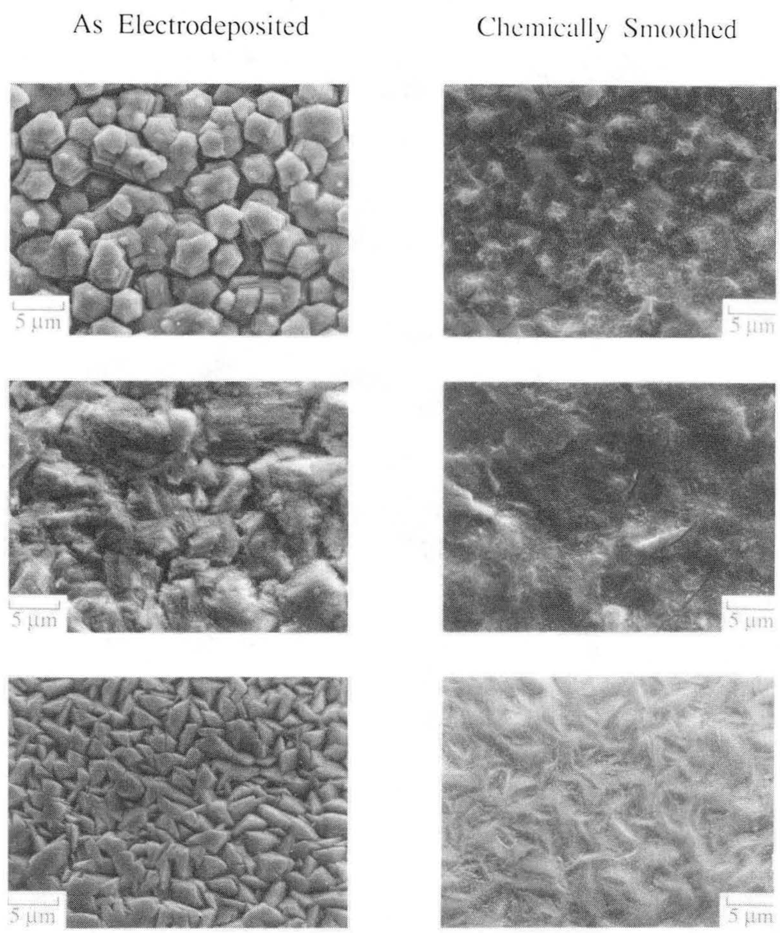

Figure 11 XBB 898-6557

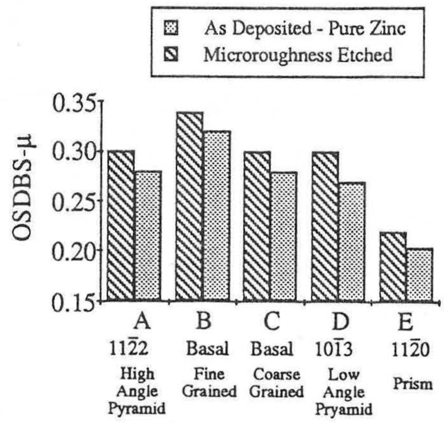

Figure 12

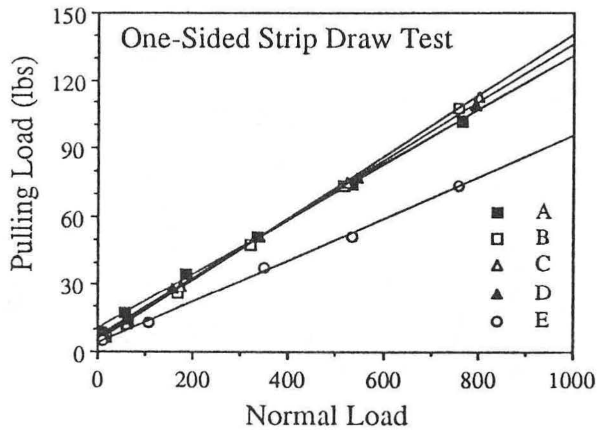

Figure 13

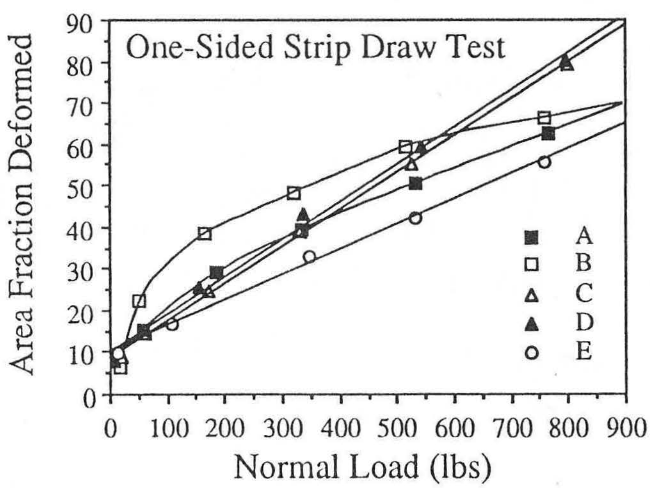

Figure 14

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