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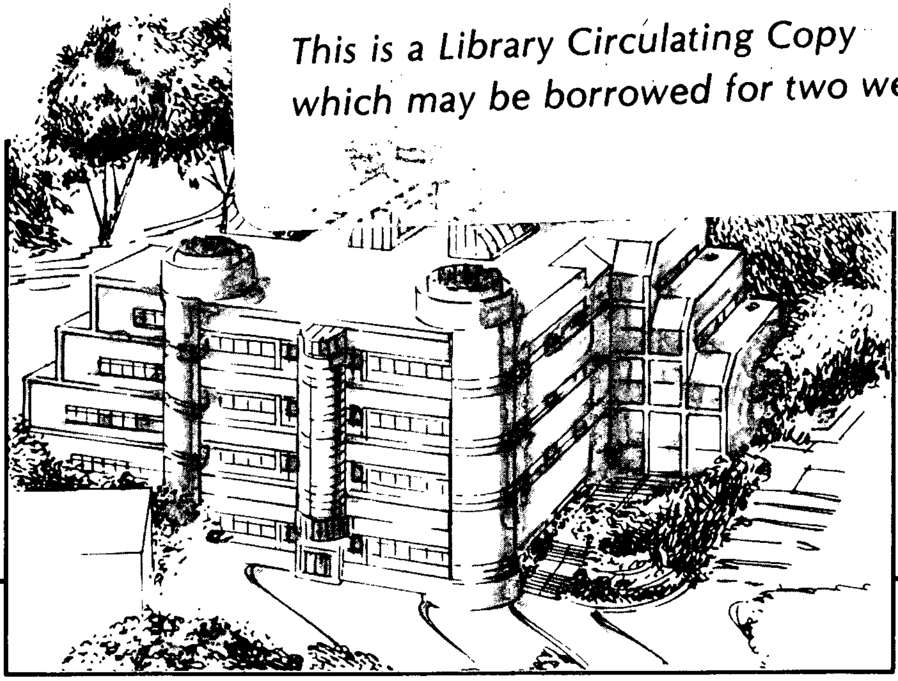

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Abstract : Significant variations are found in the measured coefficients of friction of commercial zinc electrogalvanized steel (EGS) sheets. The tribological mechanisms apparently differ from those in bare steel. Because of the relative softness of the zinc layer its mechanical properties are important in determining the coefficient of friction. Since zinc is hexagonal its mechanical properties are highly anisotropic, which suggests that the coefficient of friction should depend strongly on the crystallographic texture of the galvanized layer. Such a dependence was found in draw-bead simulator tests on a variety of commercial steels; coatings with a strong basal texture had particularly high coefficients of friction. This result is interpreted on the basis of a simple model that considers the interaction between asperities on the rigid tool and the relatively deformable coating.

Key Words: zinc electrogalvanized sheet ; coated sheet steel ; friction ; microroughness ; asperity deformation ; resolved shear stress ; texture

INTRODUCTION

The substitution of electrogalvanized steel (EGS) for cold rolled steel in the automotive industry has resulted in difficulties in the stamping plants. Electroplating does not significantly change the mechanical properties of the base steel (Table 1); the difficulty in forming is associated with excessive restraint under the binder due to increased friction. Very high coefficients of friction ($\mu \geq 0.25$) are sometimes found. Moreover, the coefficient of friction often varies from supplier to supplier and sheet to sheet, which adds to the difficulty of forming.

TABLE 1

Mechanical Properties of EGS compared to Special Killed Drawing Quality Steel Substrate.
(11 samples from 8 manufacturers)

	Y_s MPa (ksi)	UTS MPa (ksi)	e_{tot} %	n	$\bar{r}$
Good SKDQ Steel	172-207 (25-30)	289-317 (42-46)	42-48	.21-.23	1.5-2.0
EG Steels	198 (28.8)	310 (45.0)	42.1	.213	1.88

Attempts to achieve a low and reproducible coefficient of friction with the lubricants that are available for bare steel have been only partly successful. In simulative tests, for example, the use of different lubricants was often found to reverse the rankings for several different EG steels(1). While the mechanisms of friction during strip drawing of bare steel are reasonably well understood, the forming behavior of EGS is puzzling, and appears to be governed by different tribological mechanisms. These mechanisms need to be identified and understood in order that coatings which behave in a controlled, consistent, and predictable manner during stamping can be produced.

An investigation of the mechanisms of friction of electrogalvanized steel has been started in our laboratory, in collaboration with investigators at the Ford Motor Company, Rouge Steel and LTV Steel. The initial research involved drawbead simulation measurements of the coefficients of friction of a variety of commercial steels. The drawbead simulator is described in ref. (2). Friction measurements were made by strip drawing using an unformulated hydrocarbon mineral seal oil of viscosity 100 SUS. The test sample coatings were studied metallographically, and their surface roughness and crystallographic texture was determined. The results were interpreted in light of the known mechanisms of friction and the observed deformation of the electrogalvanized coating during strip drawing.

CONTRIBUTIONS TO SURFACE FRICTION

Friction strongly depends on the lubrication regime in which a process operates. Sheet forming or strip drawing operates in a mixed mode. Different regions of the surface experience metal-to-metal contact, boundary lubrication, and/or local quasihydrodynamic† lubrication. The net coefficient of friction is determined by the sum of these interactions, and can be at least roughly approximated by the areal average(4)

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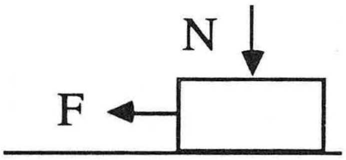
† The geometry of sheet forming is not suitable for true hydrodynamic lubrication. This requires the complete separation of the two surfaces through buildup of very high pressures via the formation of a wedge of lubricant film, as is the case for journal bearings. Recently however, Emmens(3) reported that, in bare steel, a quasihydrodynamic or "hydrostatic" lubrication effect takes place locally in the macroroughness valleys which reduces the load (or equivalently the amount of contact area) on the asperities.

$$\mu_{mix} = \mu_m \cdot A_m + \mu_b \cdot A_b + \mu_h \cdot A_h \qquad (1)$$

where A_i is the area fraction for the ith mode. The coefficients of friction for the three modes differ by about an order of magnitude: μ_m~0.1-1.0, μ_b~.01, μ_h~.001. It follows that the metal-to-metal contribution dominates if it is present to a significant degree. Lubricants are hence used to separate the two surfaces and minimize the metal-to-metal contact.

However, it is often impractical to prevent metal-metal contact in the forming of automotive sheet. Automotive sheet must be welded and painted subsequent to forming, and must meet other cosmetic requirements(5). The use of solid, dry-film type lubricants to separate the two surfaces requires difficult or economically unfeasible cleaning procedures. Conventional liquid lubricants do not completely prevent metal-metal contact between the rough surfaces of the tool and workpiece. It is, therefore, useful to modify the coating itself to reduce and control friction.

The coefficient of friction, μ, is defined macroscopically by the ratio of the pulling force (F) to the normal load (N), or, equivalently, by the ratio of the overall resistance to shearing of the interface to the resistance to compression (Figure 1). The value of μ differs, however, because of differences in the micromechanical processes that occur at the interface.



$$\mu = F/N = {}^{\tau_i}/_p$$

Figure 1) Standard Definition of coefficient of friction, τ_i = interface shear strength, p = local pressure.

EGS vs. BARE STEEL

The micromechanics of friction in electrogalvanized sheet are controlled by the nature of the interface. It is useful to note the differences between the EGS interface and that of cold rolled sheet, whose forming properties are more familiar. There are three principle differences: 1) the surface roughness, 2) the surface chemistry, and 3) the mechanical properties of the surface layer.

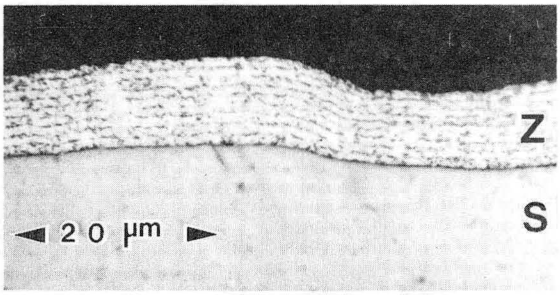


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Figure 2) Optical cross-section micrograph of commercial EG steel showing that the zinc coating (Z) parallels the macro-roughness of the steel surface (S).

The surface roughness exists on at least two geometric scales. A *macro-roughness* is imparted during temper rolling. It is defined by the hills and valleys on the sheet surface that determine the regions of metal-metal contact. The macroroughness of automotive sheet is largely fixed by distinction of image (DOI) requirements, and, under the plating conditions and thicknesses in use for automotive applications, is largely unchanged by the electrodeposition process. As illustrated in Figure 2, the zinc coating parallels the steel surface in the specimens we have investigated to date.

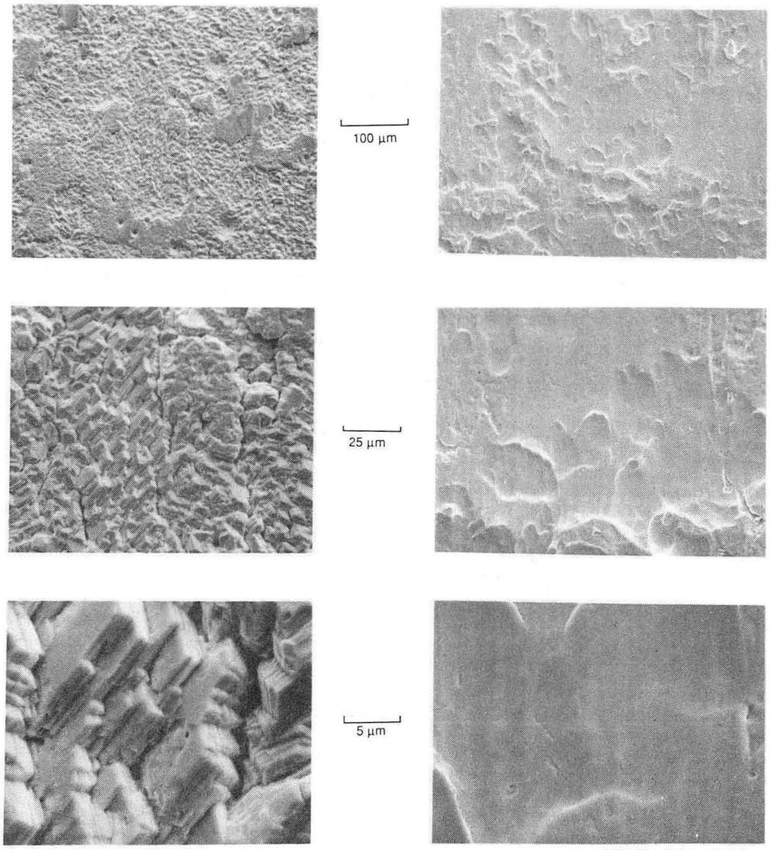

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Figure 3) Bare steel (right) has a very smooth surface below the scale of the macroroughness. EG steel (left) exhibits a distinct microroughness, superimposed on the macroroughness, due to the zinc crystallite morphology.

The surface also has a definite *microroughness* on a much finer scale. The microroughness is due to the zinc crystallite morphology. The microroughness of the galvanized surface is much greater than that of bare steel (Figure 3) and is a qualitative as well as quantitative function of the electroplating cell geometry and electroplating conditions (Figure 4). The microroughness can trap the lubricant, and should, hence, affect the hydrostatic component of the lubrication.

The change in surface chemistry on electrogalvanizing has the consequence that zinc-based rather than iron-based boundary compounds form on interaction with additives in the lubricant. These compounds will undoubtedly have different mechanical properties. More importantly however, these compounds are now supported by a soft zinc substrate. Hence the mechanical properties of the boundary compounds should be important only to the extent that they reduce sticking at the tooling/sheet asperities.

The third, and probably most important change on galvanizing is the substantial change in the mechanical properties of the surface layer. Iron is a relatively hard body-centered cubic metal (VHN>100) which is fairly isotropic in its deformation behavior. Zinc is a relatively soft (VHN<50) metal with very anisotropic plastic properties. Due to its hexagonal closed-packed (HCP) structure and high c/a ratio (1.86), slip is strongly preferred on the basal planes(6). The anisotropy of slip can be very important, since the galvanized layer often has a strong crystallographic texture that varies significantly with processing conditions during electroplating(7,8).

Direct observations of the electro-galvanized coating after strip drawing suggest that the mechanical behavior of the surface layer is the most important contribution to the coefficient of friction in the steels we have studied. Figure 5 is a typical scanning electron micrograph of the surface of the drawn sheet. The surface is dense with areas where the zinc layer has been severely deformed and flattened, presumably by metal-metal contact. This extensive deformation of the surface obliterates microroughness, and clearly involves a significant plastic work that contributes to the overall coefficient of friction. The extent of deformation and the magnitude of the plastic work that is associated with it depends on the microhardness of the zinc layer, which is, in turn, strongly dependent on its crystallographic texture. We therefore expect (and observe) a strong correlation between the measured value of the coefficient of friction and the crystallographic texture in the galvanized layer.

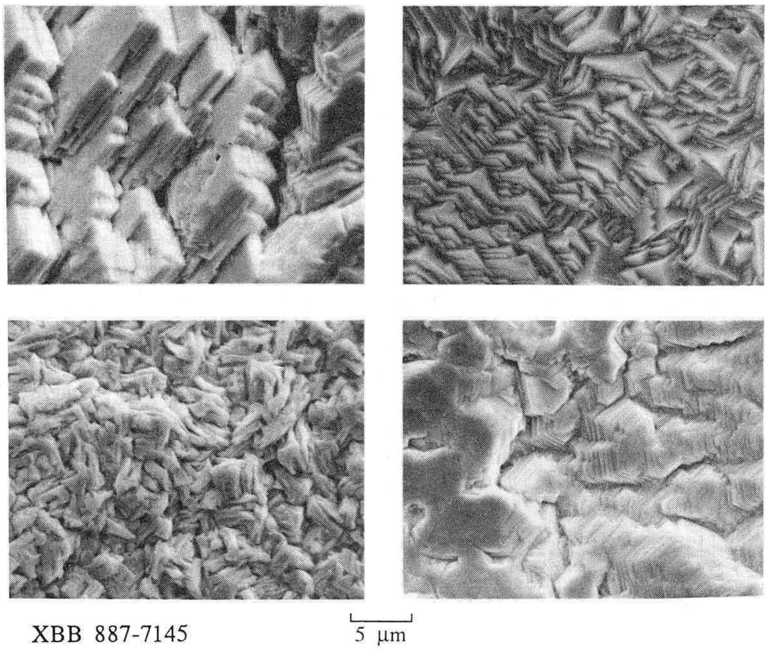


Figure 4) Variation in microroughness morphology from four different commercial EG lines. This microroughness affects lubricant channelling and load support.

THE INFLUENCE OF TEXTURE

Zinc is a hexagonal metal that deforms most easily when it is sheared in its basal plane. Referring to Figure 1, one might therefore expect that the zinc layer would shear most easily, and hence provide the least coefficient of friction, if it were textured so that its basal plane lay parallel to the plane of the sheet. In this case the zinc might behave something like a layered solid lubricant such as graphite or molybdenum disulfide.

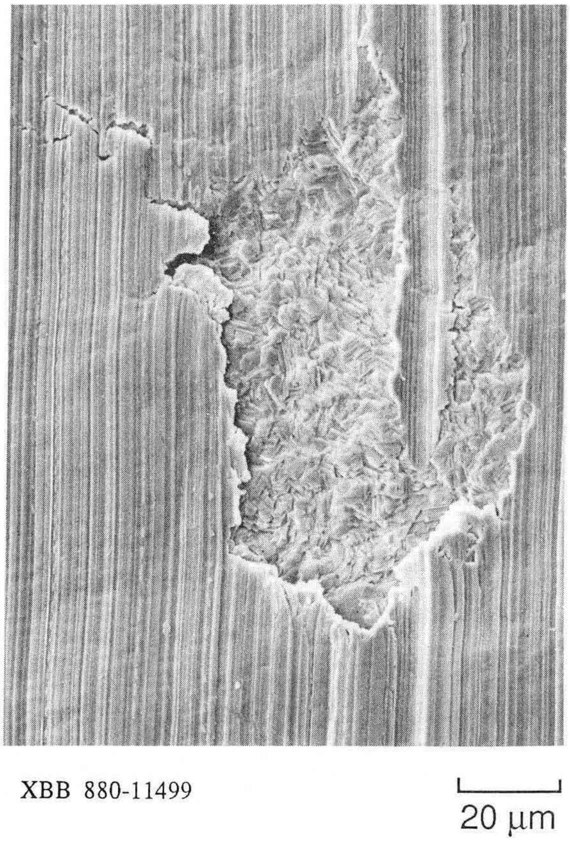


Figure 5) Soft zinc is plastically deformed during strip drawing, eliminating microroughness on asperities. Undeformed region still shows microroughness.

Contrary to this expectation, however, all commercial samples we have tested to date that had very high coefficients of friction had high proportions of basal oriented grains (determined by x-ray diffraction analysis), while those with the lowest coefficients of friction had a noticeably low or nearly absent 0002 peak. A similar conclusion was recently reported by Lindsay, et al.(9) who tested laboratory samples of two different textures, basal and "pyramid". These researchers also found that the basal texture had a much higher coefficient of friction. Their interpretation was that the microroughness of the basal orientation gave rise to a larger contact area than that of the pyramid orientation. However, this explanation cannot explain the present data since it is clear from SEM observations that the microroughness at the contact regions is obliterated by the tooling.

An alternative explanation is suggested by a closer analysis of scanning electron micrographs of the damaged surfaces, such as that shown in Figure 5. The contact areas are flattened, gouged and scratched by the tool, which shows that a substantial fraction of the plastic work of metal-metal contact is done in a digging or plowing deformation of the surface rather than the simple shear the macroscopic geometry would suggest. From this perspective, the least coefficient of friction should be associated with a surface texture that is soft with respect to the plowing action of asperities on the tool piece. The preferred texture with respect to plowing by tool asperities can be studied theoretically using simple models such as that presented below.

A SIMPLE MODEL OF THE TEXTURE EFFECT

A metal crystal deforms plastically by preferential slip on the crystallographic slip system that has the highest resolved shear stress (RSS), which is related to the imposed load by the Schmid factor(10). In zinc, slip on the basal system is at least 30 times easier than any other system(11) and hence the stress required for deformation of zinc will be controlled by the RSS on the basal system. The more strongly textured a material, the more it behaves like a single crystal. In EGS it is proposed that the friction contribution from the metal-to-metal contact will be proportional to the ease of deformation of the zinc. As such, that orientation with the highest RSS, should be the easiest to deform and hence give rise to the lowest coefficient of friction.

To analyze the ease of deformation as a function of texture we assumed that the deformation is controlled by the interaction between asperities on the tool and those on the zinc surface, and computed the RSS for a range of possible loading conditions on an asperity for several model textures. Model textures were defined by the Euler angles (Figure 6). The loading condition was varied from simple shear ($\alpha=0$) to pure compression ($\alpha=1$), using the stress tensor

$$\sigma = \begin{pmatrix} 0 & 0 & (1-\alpha) \\ 0 & 0 & 0 \\ (1-\alpha) & 0 & \alpha \end{pmatrix} \tag{2}$$

The asperity geometry on the tooling is defined by the angle λ with the plane of the sheet. Typical values of λ were determined by surface profilometry and are 5 to 10 degrees. The loading is resolved into a shearing component and a compression component as shown in figure 7. The calculation can be performed for either no sticking at the interface ($\mu' = 0$) or

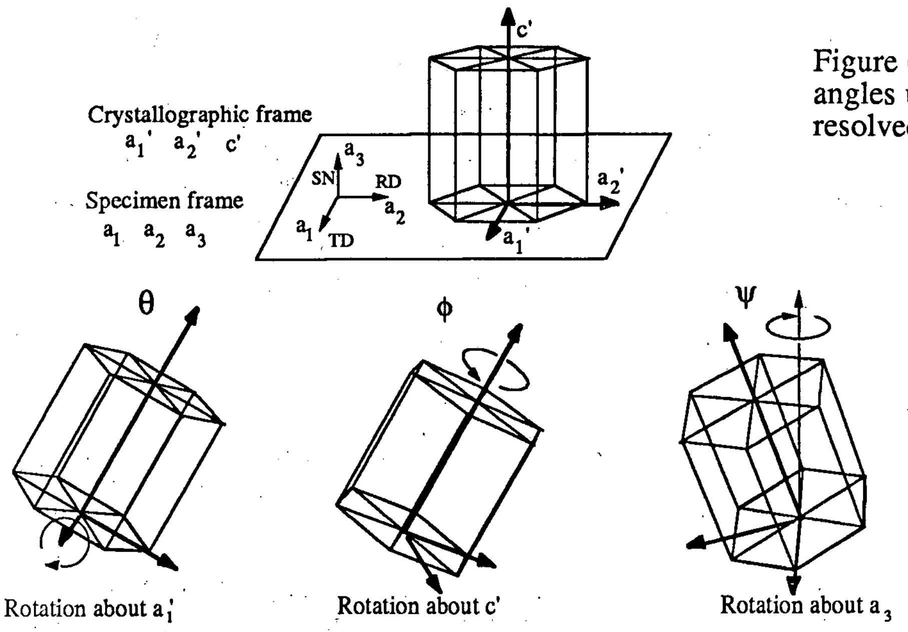
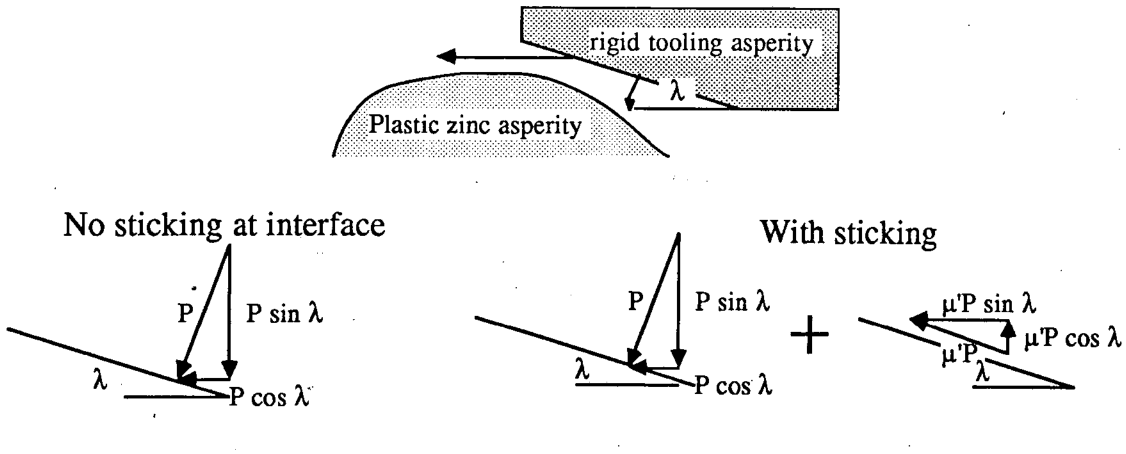


Figure 6) Definition of Euler angles used in calculations of resolved shear stress (RSS).

with some interfacial sticking. The effect of interfacial sticking is to increase the shearing component and decrease the compression component. Typically in sheet forming, due to the presence of oxides, adsorbed surface films, lubricant, etc., μ' is on the order of 0.05 to 0.25. The results of the calculations for the loading conditions are shown in Figure 8. For the range of sticking coefficients and asperity angles typically encountered, a reasonable estimate for α, the fraction of compression in the loading, is around 0.8.



$$\frac{\alpha}{(1-\alpha)} = \frac{P \sin\lambda}{P \cos\lambda} \qquad \alpha = \frac{\cot\lambda}{1+\cot\lambda} \qquad \frac{\alpha}{(1-\alpha)} = \frac{P(\sin\lambda - \mu'\cos\lambda)}{P(\cos\lambda + \mu'\sin\lambda)} = A \qquad \alpha = \frac{A}{1+A}$$

Figure 7) The loading condition (α) on a zinc asperity is determined by the rigid tooling asperity geometry. The sticking coefficient (μ') increases the shear contribution and decreases the compression contribution.

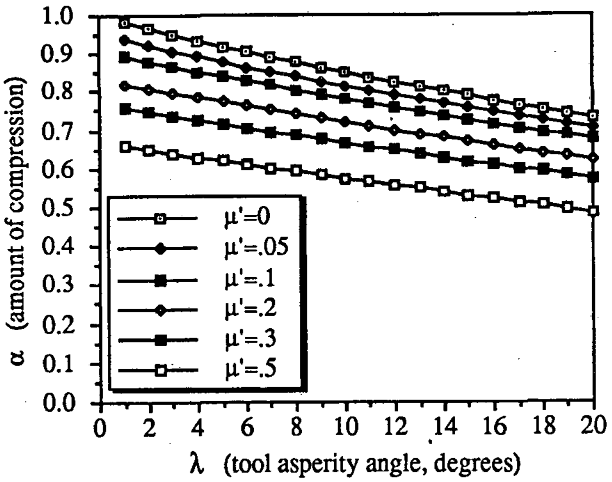


Figure 8) Results of calculations of loading condition for various tool asperity angles (λ) and sticking coefficients (μ'). Typical values of λ and μ' give α of around 0.8.

The results of the RSS calculations for three model textures are shown in figure 9. RSS_{avg} (for a fixed θ) was computed by averaging over the variations in RSS for ψ from 0 to π, thus assuming a radial symmetry about the sheet normal (fiber texture). From these calculations it can be seen that, for the loading condition imposed on a zinc asperity during strip drawing, the basal texture has an RSS of around 0.2 while that for both the $10\bar{1}3$ and $11\bar{2}2$ orientations is between 0.4 and 0.5. Thus the basal orientation is predicted to be significantly harder to deform. These results agree with the higher coefficients of friction found in commercial samples with strong basal textures. As further confirmation, laboratory prepared control samples have been produced with these three textures and are currently being tested.

The results of the model are, hence, in reasonable agreement with the experimental results; a strong basal texture of the electrogalvanized layer is associated with a relatively high coefficient of friction. It should be kept in mind, however, that other factors influence the coefficient of friction observed in practice, including particularly the macroscopic roughness, the nature of the lubricant, and, as suggested by Nine(12), possible adhesion between the zinc coating and the tool. Further investigations are in progress.

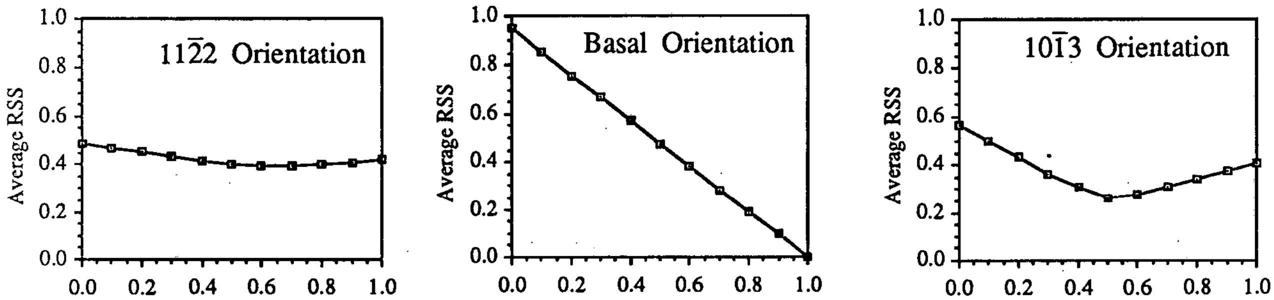


Figure 9) Results of RSS calculations for three model textures. Note that for typical loading conditions found in strip drawing (α≈0.8), both the $10\bar{1}3$ and $11\bar{2}2$ orientations have RSS values more than twice that of the basal orientation. Hence deformation of these textures is expected to be half as difficult.

CONCLUSION

The results of this initial work suggest that the texture of the zinc layer is an important factor in determining the coefficient of friction of electrogalvanized steel. In particular, a strong basal texture yields a high coefficient of friction. The source of this behavior apparently lies in the significant plastic deformation of the zinc layer that occurs during drawing. The work of plastic deformation is largely due to the plowing of tool asperities through the zinc layer. A simple model was proposed to treat this effect. The model predicts that basal textured EGS has a higher resistance to deformation than sheet textured in either the $10\bar{1}3$ or $11\bar{2}2$ orientations. The results are in agreement with prior work on control samples by Lindsay, et al.(9), and suggest that the formability of electrogalvanized steel can be improved by adjusting the process parameters to impart a desirable texture to the zinc layer.

ACKNOWLEDGEMENT

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