Title
Cracking of Textured Zinc Coating During Forming Process

Authors
Mei, Z.
Morris, J.W.

Publication Date
1993-09-01

LBL-34795
UC-404

Lawrence Berkeley Laboratory
UNIVERSITY OF CALIFORNIA

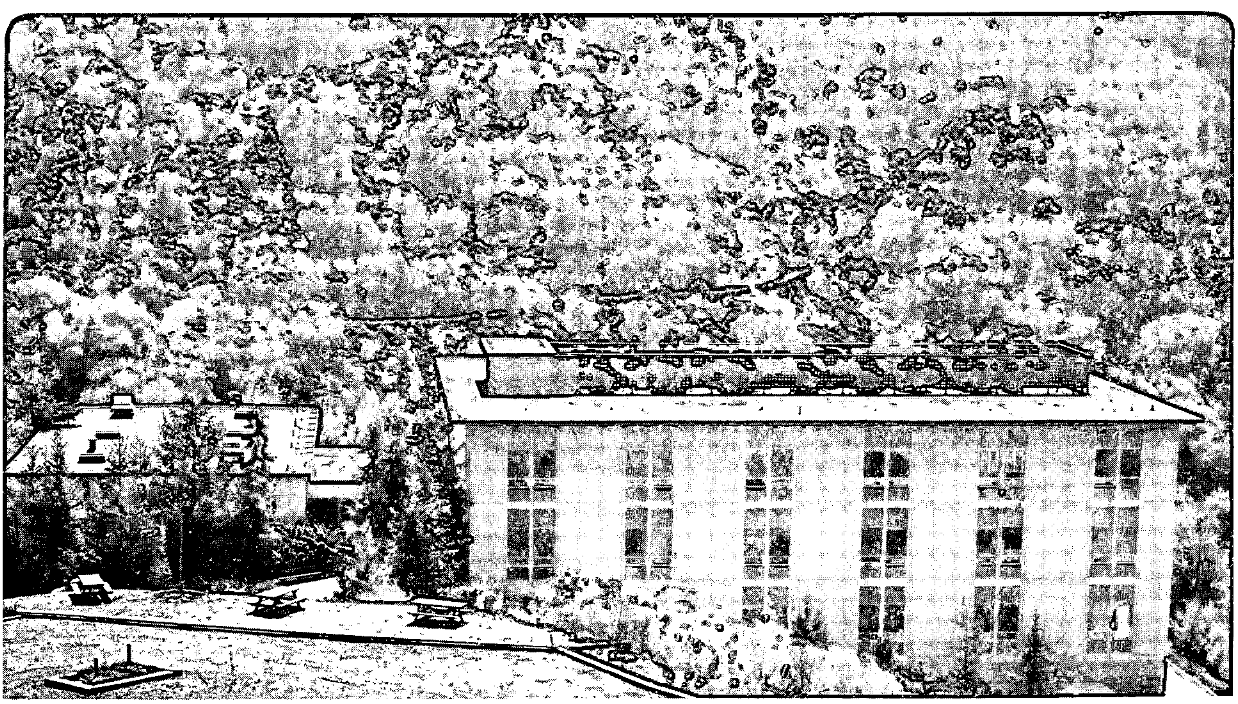
Materials Sciences Division

To be presented at the International Symposium on the Physical Metallurgy of Zinc Coated Steels: Processing, Structure and Properties, San Francisco, CA, February 28–March 3, 1994, and to be published in the Proceedings

Cracking of Textured Zinc Coating during Forming Process

Z. Mei and J.W. Morris, Jr.

September 1993



Prepared for the U.S. Department of Energy under Contract Number DE-AC03-76SF00098

DISCLAIMER

LBL 34795

CRACKING OF TEXTURED ZINC COATING

DURING FORMING PROCESS

Z. Mei and J. W. Morris, Jr.

Center for Advanced Materials
Materials Sciences Division
Lawrence Berkeley Laboratory
University of California
Berkeley, CA 94720

and

Department of Materials Science and Mineral Engineering
University of California

September 1993

This work was supported by the Director, Office of Energy Research, Office of Basic Energy Science, Materials Science Division of the U.S. Department of Energy under Contract No. DE-AC03-76F00098

CRACKING OF TEXTURED ZINC COATING

DURING FORMING PROCESS

Z. Mei and J.W. Morris, Jr.

Center for Advanced Materials, Lawrence Berkeley Laboratory and
Department of Materials Science and Mineral Engineering
University of California, Berkeley, CA 94720

Abstract

A model is presented to relate cracking of a zinc coating on steel during forming process with its crystallographic texture. There are three deformation modes that can accommodate strains in a zinc coating caused by external loadings: basal slip, twinning, and cleavage cracking. Twinning of a zinc hexagonal crystal induces a contraction along its c-axis while cleavage relaxes tensile strain along its c-axis. Because of this, when basal slip in grains of a textured zinc coating is difficult under a given loading, either twinning or cleavage occurs, depending on whether the basal plane is parallel or normal to the loading axis and whether the loading is tensile or compressive. The loadings during formability or surface friction tests cause twinning in the basal-textured coating and cleavage cracking in the prism-textured coating. The prism-textured coating contains an extraordinarily high hardness since none of the three deformation modes may be operative under compression. These results derived from the model are confirmed with recent studies on electrogalvanized steels.

The authors appreciate valuable discussions with Mr. P. Skarpelos and Ms. P.A. Kramer at Lawrence Berkeley Laboratory. This work was supported by the Ford Motor Company and Rouge Steel Company through a joint research gift to the Center for Advanced Materials, Lawrence Berkeley Laboratory, and by the Director, Office of Energy Research, Office of Basic Energy Science, Materials Sciences Division of the U.S. Department of Energy under Contract No. DE-AC03-76SF00098.

Introduction

The use of zinc-coated steel has dramatically increased in recent years due to the market demand for corrosion resistant automobiles. Zinc coating over steel sheet is usually produced through either hot dip or electrodeposition, and often possesses crystallographic textures - zinc grains in the coating are oriented preferentially with respect to geometrical directions of the sheet. Various kinds of zinc coating textures can be produced by adjusting the processing parameters - matrix texture, additives in electrodeposition bath, bath temperature, electrodeposition current density, and so on [1-3]. Zinc has a hexagonal crystal structure; its deformation behaviors are highly anisotropic. Mechanical properties of a zinc coating are therefore influenced by its crystallographic texture.

As reported in recent studies on formability and tribology of zinc-coated steels [4-11], some specimens sustained relatively large plastic strains while others formed extensive surface cracks in zinc coatings (Figure 1, as an example), after they were tested by either uniaxial tension, axisymmetric stretch, bending under tension, or drawbead simulation (a combination of bending and surface friction). Textures of the specimens that sustained large plastic deformations were seen to change into different ones, while textures of the specimens that formed surface cracks remained the same after the tests. There is a general consensus in these studies that when the coating texture is oriented such that glide along slip planes is difficult, the deformation required by the external loading is accommodated through cracking. Both Safranek [11] and Suk-Wan Pak & M. Meshii [9] have pointed out that under a uniaxial tension, cracking occurs when the deformation axis is approximately perpendicular to the (0001) plane, the so-called prism texture. Twinning is also a possible deformation mode, and was used to explain the texture evolution of zinc coatings during surface friction tests at room temperature [12]. Another related observation was the extraordinarily high hardness for the prism-textured zinc coating compared with coatings of other textures [12] (Figure 2), which is probably the reason for the prism-textured zinc coating to have the lowest friction coefficient among various textured coatings [12].

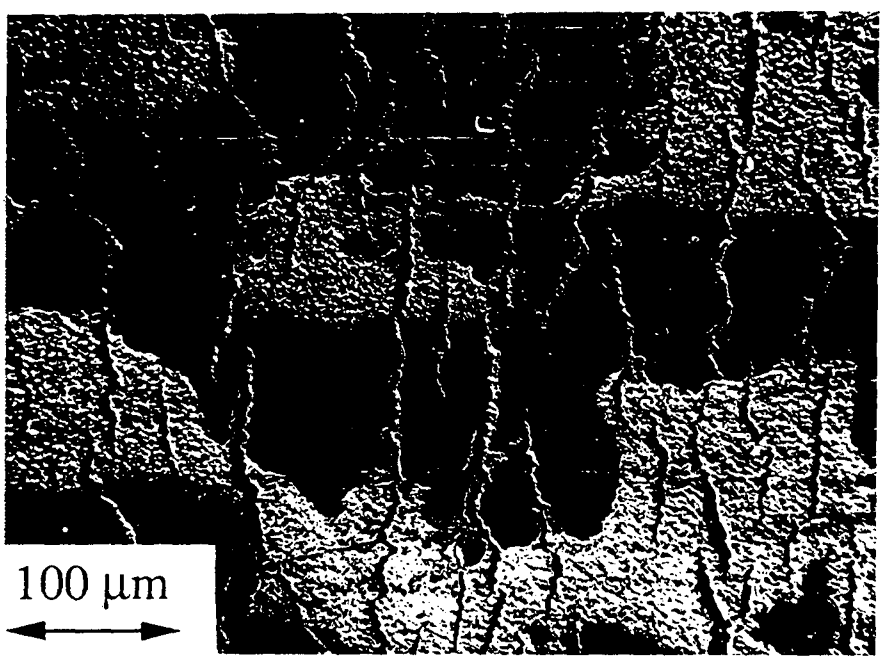


Fig.1: Cracking of zinc coating after drawbead simulation test of a commercial, near prism-textured electrogalvanized steel.

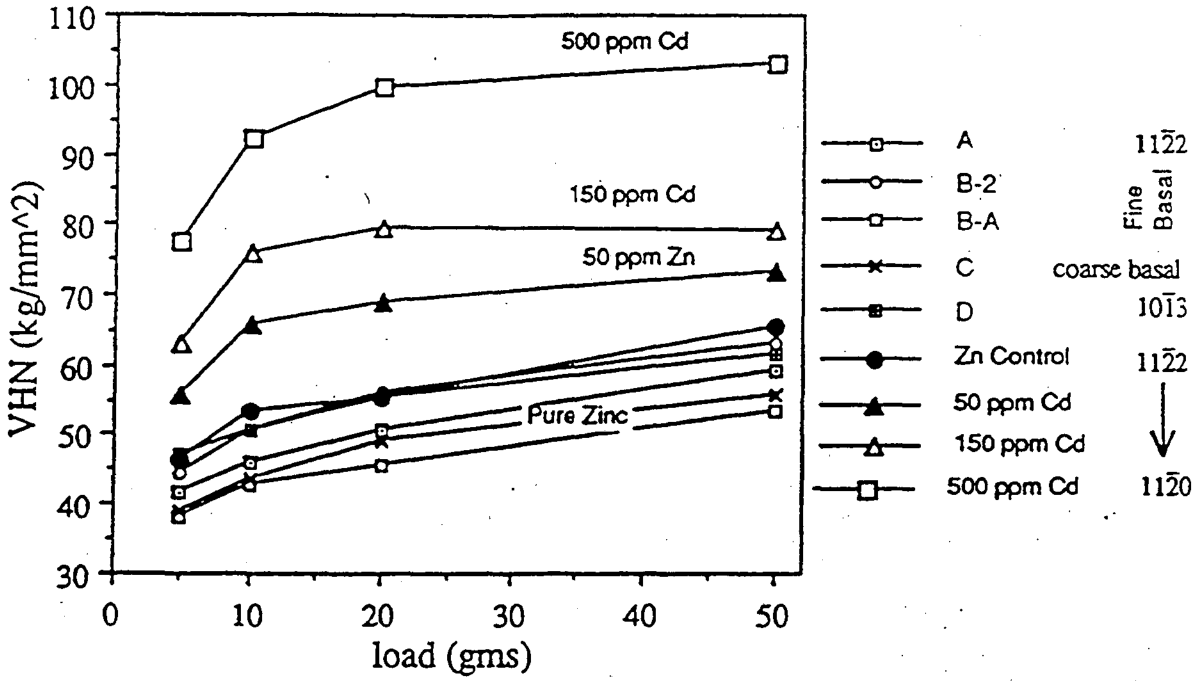


Fig.2: Hardness of pure zinc and Cd-doped electrogalvanized coatings, after Shaffer [12].

The work reported here attempts to explain the above-mentioned experimental observations on the texture dependence of cracking and hardness of zinc coatings, based on an analysis of the deformation modes in a zinc crystal, and their relations with the zinc-coating textures and the external loadings. We first describe the deformation modes in a zinc crystal especially the complementary nature of twinning and cleavage, and then identify the predominant deformation modes for different situations where various textured zinc coatings are subjected to different loadings. As results, the coating texture that most likely causes surface cracking during forming operations and the texture that may contains the highest hardness are recognized and explained.

Deformation Modes of Zinc Coating

There are at least three deformation modes that can accommodate the strain in zinc coating required by external loadings: slip, twinning, and cracking.

Slip

Slip in zinc usually occurs on the basal plane (0001) and along $<11\bar{2}0>$ directions [13]. Another slip system, pyramidal slip $\{\bar{1}122\}$ $<\bar{1}123>$, was also observed in a single zinc crystal at room temperature, and is associated with the nucleation of a mechanical twin [14]. However, the critical resolved shear stress to initiate slip in this system is about 50 times larger than that for basal slip [14]. Prism slip $\{\bar{1}010\}$ $<\bar{1}120>$ was reported only at high temperatures (above 250°C) [15], and therefore will not be considered here.

Twinning

Mechanical twinning in zinc crystals occurs only on $\{\bar{1}012\}$ planes along $<10\bar{1}1>$ directions. Twinning deformation is usually described in the literature [16,17] by defining K_1, K_2 planes and η_1, η_2 directions. Shown in Figure 3 is a spherical single crystal, where its upper hemisphere is sheared into a half ellipsoid by twinning along the η_1 direction in the K_1

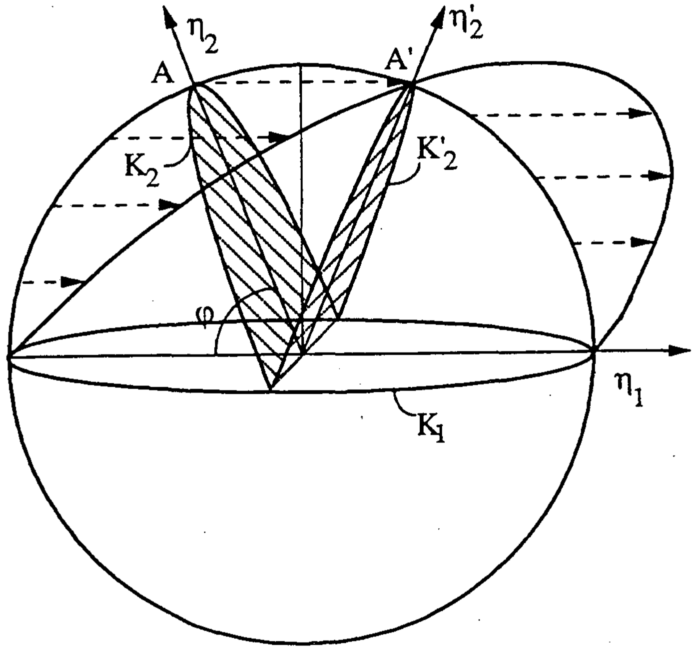


Fig.3: A spherical single crystal, where its upper hemisphere is sheared into a half ellipsoid by twinning along η_1 direction in the K_1 plane.

plane. Besides the K_1 plane, the only other plane that is not distorted during twinning is the K_2 plane. The plane which is perpendicular to both K_1 and K_2 is defined as the plane of shear. The intersection between the plane of shear and K_2 is the direction η_2. With the help of Figure 3, it is seen that, in the plane of shear, any direction in the untwinned crystal that lies between η_2 and η_1 increases in length after twinning; any direction that is located between the opposite direction of η_1 and η_2 decreases in length after twinning.

The planes K_1, K_2, and the directions η_1, η_2 for zinc crystals come from combinations of the families $\{\bar{1}012\}$ and $<10\bar{1}1>$. A specific example is illustrated in Figure 4 where K_1, K_2, η_1, and η_2 are chosen to be $(10\bar{1}2)$, $(\bar{1}0\bar{1}2)$, $[10\bar{1}\bar{1}]$, and $[10\bar{1}1]$, respectively. The shear strain, s, due to twinning is calculated from ϕ, the angle between K_1 and K_2, through the formula [16],

$$s = \frac{2}{\tan \phi} \tag{1}$$

For zinc (c/a ratio =1.856, [13]) ϕ is roughly 86°, and s is therefore approximately 0.138. This value, the twinning strain in zinc, is much smaller than the twinning strain for a typical cubic crystal (fcc or bcc) of 0.707, which is why twinning is a relatively easy process in zinc compared with most cubic crystals.

The change in length, L'/L, where L is the length along a direction in an untwinned crystal and becomes L' after twinning, is calculated by the following equation [16],

$$\frac{L'}{L} = (1 + 2\,s \sin\chi \cos\lambda + s^2 \sin^2\chi)^{1/2} \tag{2}$$

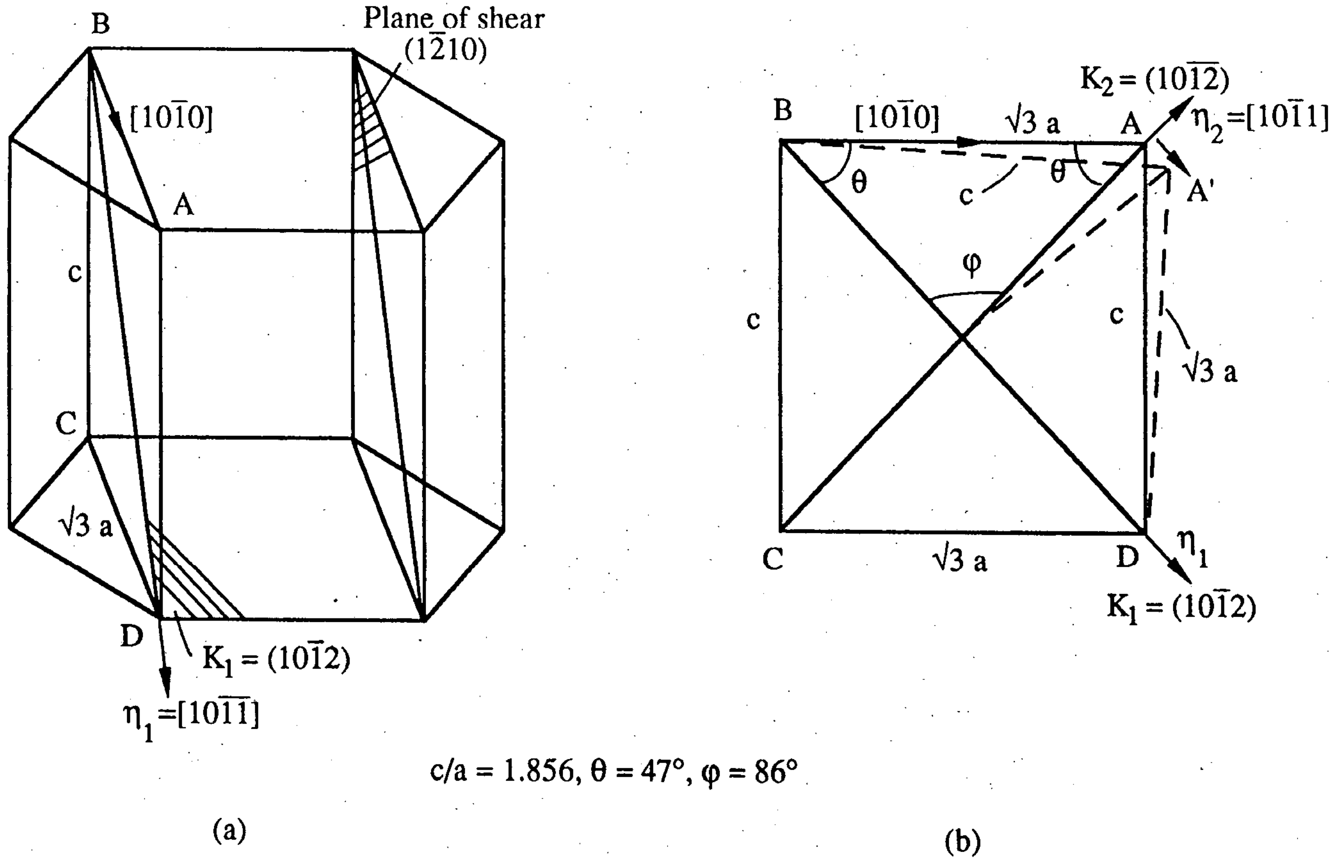


Figure 4: Schematic description of twinning deformation in zinc. (a) Twinning plane K_1 and direction η_1; (b) On the plane of shear, the triangle BAD changes into BA'D after twinning, and [10$\bar{1}$0] in the untwinned crystal becomes the c-axis in the twinned crystal.

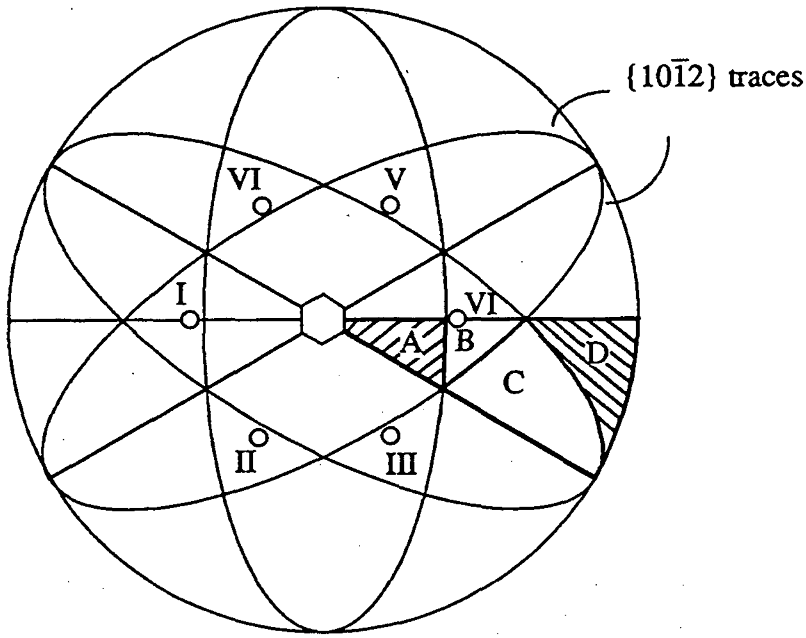


Figure 5: Stereogram for twinning in zinc (after Hall [16]).

I - VI, poles of twin planes
A. I - VI compression
B. II, III, V, and VI compression; I and IV extension
C. II and V compression, others extension
D. I - VI extension

where λ is the angle between L and η_1, χ is the angle between L and K_1 plane. If L is on the plane of shear, λ is equal to χ. With (2), the directions in untwinned crystal can be divided into several regions, as shown in Figure 5 of the stereographic projection. The six potential twin plane poles {$\bar{1}$012} are marked I through VI. Any direction in region A, which is around the basal plane pole, shortens after twinning on any of the six twinning planes. Any direction in region D elongates after twinning on any of the six twinning planes. Directions in regions B and C shorten or elongate depending on which twinning plane is operative.

Cracking

There are two possible cracking mechanisms: cleavage and intergranular cracking. Cleavage in a zinc single crystal was observed to occur exclusively on the basal plane [18,19], because of its larger than ideal c/a ratio (1.856 > 1.633). Intergranular cracking in metals usually results from either grain boundary movement at high temperature or from residual element segregation at grain boundaries. For zinc with melting point of 420°C, grain boundary movements are unlikely when a zinc-coated steel is formed at room temperature with a relatively high speed. But even a small amount of detrimental elements in electrodeposition bath may cause a significant segregation at zinc grain boundaries. Despite various possibilities, no clear evidence of intergranular cracking in zinc coating has been reported so far.

Kinking

This mode was observed when a single zinc crystal rod was compressed almost parallel to its basal plane, as described in [20,21]. This mode is not considered here because as written in [14], Bell and Cahn had reached an agreement with Gilman, the author of [21], that kinking is actually pyramidal slip on $\{\bar{1}122\}$.

Conditions for Cracking in Zinc Coating

Of the three deformation modes, the one which is operative under a given loading is determined by the resolved stresses - the resolved shear stress on the slip plane along the slip direction, the resolved shear stress on the twinning plane along the twinning direction, and the resolved normal stress on the cleavage plane; and also determined by the inherent resistant strengths of the zinc coating to the three modes. For a zinc crystal, slip on the basal plane is much easier than either twinning or cleavage. Therefore, unless the grains in the zinc coating are oriented very unfavorably for slip, i.e., the resolved shear stress for slip is very small, slip on the basal plane is always the predominant deformation mechanism. The two unfavorable orientations for basal slip are when the deformation axis is either parallel or normal to the basal plane. For these two orientations there is no close competition between twinning and cleavage; each of the modes has its own territory. Cleavage can accommodate only *tensile* strain normal to the basal plane; while twinning can accommodate only *compressive* strain normal to the basal plane (Figure 5).

Suppose a zinc-coated steel sheet is being stretched. If the zinc coating has a prism texture - the c-axis of the zinc lattice is parallel to the sheet plane, there may be some grains with their c-axes parallel to the tensile axis. For those grains, twinning is impossible since it shortens the c-axis; the choice left is either cleavage or intergranular cracking. If the zinc-coating has a basal texture - the c-axis is normal to the sheet plane, since the resolved normal stress on the basal plane is zero, cleavage is impossible; the choice left is competition between twinning and intergranular cracking. If twinning occurs instead of intergranular cracking, the lattice orientation changes. As shown in Figure 4, after twinning, the $[10\bar{1}0]$ vector in the untwinned crystal becomes the c-axis [0001] in the twinned crystal, and vice versa. The angle between the two c-axes in the twinned and untwinned crystals is about 86°. Therefore, twinning improves the chance for basal slip, but not by very much; the c-axis in the untwinned crystal changes from that normal to the sheet plane to that in twinned crystal almost parallel to the sheet plane. The situation for the twinned crystal is just like what was discussed for a prism texture, i.e., the grains with their c-axes parallel to the tensile axis proceed cracking. In comparison, a prism-textured coating has a much higher chance for cracking than a basal-textured coating.

If a zinc-coated steel sheet is going through a drawbead or being tested with bending under tension, in addition to the tensile and compressive strains due to bending and unbending, the coating experiences stamping on the sheet plane and friction between the coating and the tool piece. Since the effect of tensile strain on the crack formation was discussed above, here we concentrate on cracking under stamping and friction loads. If a zinc coating has a prism texture, then under stamping force alone twinning cannot occur, because it causes elongation along sheet plane normal. Cleavage is not possible either, because the resolved normal stress on the basal plane is zero. The zinc coating with prism texture is expected to have a high hardness. Shaffer [12] reported that the prism-textured coating had the highest hardness among coatings of various textures. The prism-textured coating was produced by introducing 500 ppm cadmium into pure zinc. However, the extraordinarily high (about twice of the other textured coatings, Figure 2) hardness in the prism-textured coating cannot be due to the alloying effect alone and is probably related to the texture effect discussed here. If the interface between the prism-textured zinc coating and the tool piece is not well lubricated, frictional force can cause cracking just like the tensile stress discussed above. For a basal-textured zinc coating, the stamping force causes twinning instead of cleavage, which orients grains for possible cleavage cracking by the frictional force. Again, a prism-textured coating is more likely to cause cracking than a basal-textured coating.

Although a prism-textured coating may cause cleavage under tensile loading, it does not always do so. The prism texture only defines the c-axis being parallel to the sheet plane and does not regulate direction the c-axis is aligned to. For an extreme case where all grains in the prism-textured coating align their c-axes normal to the tensile axis, twinning rather than cleavage occurs. In recent studies of zinc-coated steel [4-11], all texture measurements or descriptions were limited to the angle between the basal plane normal and sheet plane normal; apparently this kind of measurement and description obtains major but not all relevant texture information for cracking behavior.

The experimental observations of cracking in zinc-coated steel during forming processes are in general agreement with the above analysis. Lindsay, et al. [4] at General Motors did draw-cup and drawbead simulation tests on electrogalvanized steels with two zinc coatings of basal and prism textures. They observed cracking in the prism-textured coating not in the basal-textured coating. Shaffer, et al. [6] observed cracks on electrogalvanized steel with a texture close to prism but not on steel with pyramidal texture, after 25% tensile strain. Deits and Matlock [7] did flat-bottom cup deep-drawing tests on electrogalvanized steel with coatings of $(10\bar{1}3)$ texture (basal plane is at 35° with sheet plane) and $(10\bar{1}1)$ texture (basal plane is at 65° with sheet plane). Surface cracks were observed on the $(10\bar{1}1)$ textured coating not on the $(10\bar{1}3)$ textured coating. Pak and Meshii [8,9] did axisymmetric stretch forming tests by punching on 9 kinds of electrogalvanized steel sheets with different coating thickness and textures. Only the sheets with prism textures revealed surface cracks. The only observations that contradict the above analysis were done by Rangarajan et al. [5,10]. In their tensile tests [5] of galvanized steel sheet with pyramidal textures and hot dip 95%(wt)Zn-5%Al coated steel sheet with basal texture, surface cracks formed in the latter not in the former. 95%Zn-5%Al is an eutectic composition, which makes the case complicated. In [10], they performed bending under tension friction tests on electrogalvanize steel with coating of pyramidal $(10\bar{1}3)$ texture and hot dipped coating with basal texture. Cracks were observed in the hot dipped coating but not in the electrogalvanized coating. The result is probably due to the different grain sizes in the hot dip and electrodeposited coatings; hot dipping generates grains of much larger size.

Discussion

The above analysis of cracking behavior in zinc coating is based on the deformation mode partition of single zinc crystal. The idea is simple but can qualitatively explain most experimental observations. The same idea may be used to analyze other mechanical behaviors of zinc coating, such as plasticity, deformation-induced texture development, and friction. A similar approach may also be adopted to other coatings of hcp metals. However, other factors that influence cracking behavior in zinc coating that were not considered in the model above need to be discussed here.

Nonuniform Stress

When a zinc-coated steel sheet is under uniaxial tension, the stress distribution in the coating is not uniform along the thickness direction. A shear stress develops at the coating / matrix interface. When a zinc-coated steel sheet is subjected to stamping, the stress distribution depends on the morphologies of the surface asperities in contact and on lubrication. If the stress distribution is known, the resolved stresses for slip, twinning and cleavage may be accurately calculated.

Polycrystal

A textured zinc-coating is still polycrystalline. To fully fix a grain orientation in space, two coordinate angles are needed. But experimentally determined textures of zinc coatings usually specify only one lattice direction or plane aligning with sheet normal direction. An individual grain in zinc coating deforms under the influence of both external loading and constraint forces from neighbor grains to keep strain continuity at the grain boundaries. At least five deformation systems are needed to maintain grain boundary continuity for a randomly oriented grain agglomerate. For a textured polycrystal coating, less than five systems are necessary, because the strain that is required to accommodate neighbor grains is restricted by common texture. For grains on the surface, only two systems are necessary because there are only two independent variables in any plastic strain tensor for a two-dimensional space. Only two of the three basal slip systems are independent, therefore for grains not on the surface, twinning is always involved in deformation. However, unlike slip, twinning provides shearing along only one direction, and may not satisfy a required accommodation strain, resulting in cleavage.

Critical Resolved Stresses

The Schmid's law that slip commences as the resolved shear stress on a slip plane along a slip direction reaches a critical value, was confirmed in a zinc single crystal with the measured critical value 0.18 MPa [22]. For twinning in a zinc single crystal, it was observed [14] that among the six twinning systems $\{\bar{1}012\}$, the one that came into action was the one with the maximum resolved shear stress. However, no single critical shear stress existed for twinning; this stress depended on orientation with respect to the loading axis. The phenomenon was related to twin nucleation which occurred after a certain amount of slip at both basal and pyramidal planes, resulting in an avalanche of twins. When a single crystal was oriented to allow a certain amount of basal slip, the resolved shear stress on the twinning plane along the twinning direction to start twinning became lower. The resolved shear stress measured at room temperature ranged between 10 and 40 MPa for carefully prepared single crystals [14]. For crystals containing small twin nuclei due to accidental damage, the resolved shear stresses were between 3 and 5 MPa [14]. Similar to twinning, a careful study of cleavage in a single zinc crystal [18] showed that the Sohncke's law that a critical value of the stress normal to cleavage plane is necessary to cause cleavage fracture, did not hold. Sohncke's law is valid for crystals that are subject to very little prior plastic deformation. For a single zinc crystal being pulled to fracture, the plastic deformation before final cleavage varied between 0 and 40%, depending on lattice orientation with respect to the loading axis, and values of the resolved normal stress on the cleavage plane at fracture were seen to change from 5 to 0.5 MPa [18].

Conclusion

Twinning of a zinc crystal causes a contraction along its c-axis while cleavage relaxes tensile strain along its c-axis. Because of this, when basal slip in grains of textured zinc coating is difficult under a given loading, either twinning or cleavage cracking occurs, depending on whether the basal plane is parallel or normal to the loading axis and whether the loading is tensile or compressive. Cleavage takes place when the basal plane is normal to the tensile axis; twinning occurs when the basal plane is either normal to the compression axis or parallel to the tensile axis; neither twinning nor cleavage occur when the basal plane is parallel to the compression axis, resulting in an extraordinarily hard coating.

References

[1] I. Tomov, Chr. Cvetkova, V. Velinov, A. Riesenkampf, and B. Pawlik, J. Appl. Electrochemistry, vol. 19, (1989), 377-382.

[2] R.D. Naybour, Electrochimica Acta, vol. 13, (1968), pp. 763-769.

[3] A. Weymeersch, R. Winand and L. Renard, Plating and Surface Finishing, vol. 68, no. 5, (1981), pp. 118-120.

[4] J.H. Lindsay, R.F. Paluch, J.D. Nine, V.R. Miller and T.J. O'Keefe, Plating and Surface Finishing, vol. 76, no. 3, (1989), pp. 62-69.

[5] V. Rangarajan, N.M. Giallourakis, D.K. Matlock, and G. Krauss, J. Mater. Shaping Technol., vol. 6, (1989), pp. 217-227.

[6] S.J. Shaffer, J.W. Morris, Jr., and H.-R. Wenk, in Zinc-Based Steel Coating Systems: Metallurgy and Performance, G. Krauss and D.K. Matlock, eds., TMS, Warrendale, PA, (1990), pp. 129-140.

[7] S.H. Deits and D.K. Matlock, ibid, pp. 297-317.

[8] Suk-Wan Pak and M. Meshii, ibid, pp. 341-355.

[9] Suk-Wan Pak and M. Meshii, ibid, pp. 357-369.

[10] V. Rangarajan, D.K. Matlock, and G. Krauss, ibid, pp. 263-280.

[11] W.H. Safranek, in The Properties of Electrodeposited Metals and Alloys, second edition, American Electroplaters and Surface Finishers Society, Orlando, Florida (1986), pp. 459-470.

[12] S.J. Shaffer, Ph.D. Thesis, University of California at Berkeley, 1990.

[13] R.W.K. Honeycombe, in The Plastic Deformation of Metals, second edition, Edward Arnold, London, (1984), p. 114.

[14] R.L. Bell and R.W. Cahn, Proc. Roy. Soc., (1957), vol. 239, p.494.

[15] J.J. Gilman, Trans. Am. Inst. Mining, Met., Petrol. Engrs., vol. 206, (1956), pp. 1326-1336.

[16] E.O. Hall, in Twinning, Butterworths Scientific Publications, London, 1954.

[17] Deformation Twinning, R.E. Reed-Hill, J.P. Hirth, and H.C. Rogers, eds., Gordon and Breach Science Publishers, New York, 1964.

[18] A. Deruyttere and G.B. Greenough, Institute of Metals, vol. 84, (1955-1956), pp. 337-345.

[19] J.J. Gilman, Trans. Amer. Inst. of Min. (Metall.) Engrs, vol. 203, (1955), pp. 1252-1254.

[20] R.W.K. Honeycombe, in The Plastic Deformation of Metals, second edition, Edward Arnold, London, (1984), p. 200.

[21] J.J. Gilman, Trans. Amer. Inst. of Min. (Metall.) Engrs, vol. 203, (1955), pp. 206-214.

[22] D.C. Jillson, Trans. Amer. Inst. of Min. (Metall.) Engrs, vol. 188, (1950), p. 1129.