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Deformation Behavior of Hot Dip Galvanized Coatings in Complex Sheet Metal Forming

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Abstract. The hot dipped galvanized coatings of flexible tubes with variable corrosion resistances were examined by x-ray diffraction and scanning electron microscopy (SEM). Accelerated corrosion was related to wide cracks formed during roll forming of coatings with coarse spangle sizes and preferred orientation of Zn basal planes parallel to the coating surface. Coarse spangled coatings with reduced preferred orientation of basal planes parallel to sheet surfaces formed only thin cracks and accommodated forming strain primarily by plastic flow. Coatings with fine spangle sizes and preferred parallel basal plane orientations developed networks of fine cracks during forming. The zinc coatings with fine cracks did not expose sufficient steel to cause accelerated galvanic corrosion.

Introduction

Zinc based coatings provide barrier and sacrificial corrosion protection to steels [1–4]. The extent of corrosion protection depends on the uniformity of coating coverage and coating weight or thickness. Sacrificial anodic corrosion results in the preferential corrosion of zinc and protection of exposed steel. The extent of such galvanic corrosion depends on coating coverage, that is, the ratio of areas of steel and zinc that are exposed to the environment. With the expanded use of galvanized sheet steels in automobiles, the effects of coating properties and forming operation on the ability to maintain complete coverage in formed parts is of significant current interest.

Recently, the flow and fracture behavior of various zinc based coatings have been related to their crystallographic texture [5]. For example, electrogalvanized zinc coatings with nonbasal plane textures exhibit plastic deformation during uniaxial tension tests, while coatings with strong basal plane texture, such as Galfan, (a Zn-Al alloy coating) exhibited extensive cracking. The limited basal plane slip systems were favorably oriented for slip in the coatings with nonbasal plane texture, while the opposite was true for the coatings in which basal planes were largely parallel to the sheet surface [5].

This paper presents results of an investigation which demonstrates the importance of texture and crack formation during forming on the subsequent atmospheric corrosion of hot dip galvanized parts. Specifically, an analysis of the corrosion behavior in galvanized parts revealed that flexible tubes made from certain batches of hot dip galvanized steel with relatively large spangle sizes corroded rapidly on localized areas of the parts. The zinc corrosion products, in the form of a fine white powder containing oxides and hydroxides of zinc [4], developed rapidly in storage and prior to service. In contrast, parts formed from other coated steels with either coarse or fine spangles had acceptable corrosion resistance. Based on previous work [5], it was hypothesized that the corrosion responses of the different hot dip zinc coatings were due to texture effects, in addition to

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Table 1. Spangle Size and Texture of Hot Dip Zinc Coatings

Coating Code	Rel. Spangle Size	Rel. Basal Tex.
X	Large	Moderate
Y	Large	Strong
Z	Small	Very strong

the effects of spangle size. To evaluate this hypothesis, three coated materials which were formed in a commercial forming operation were selected for analysis.

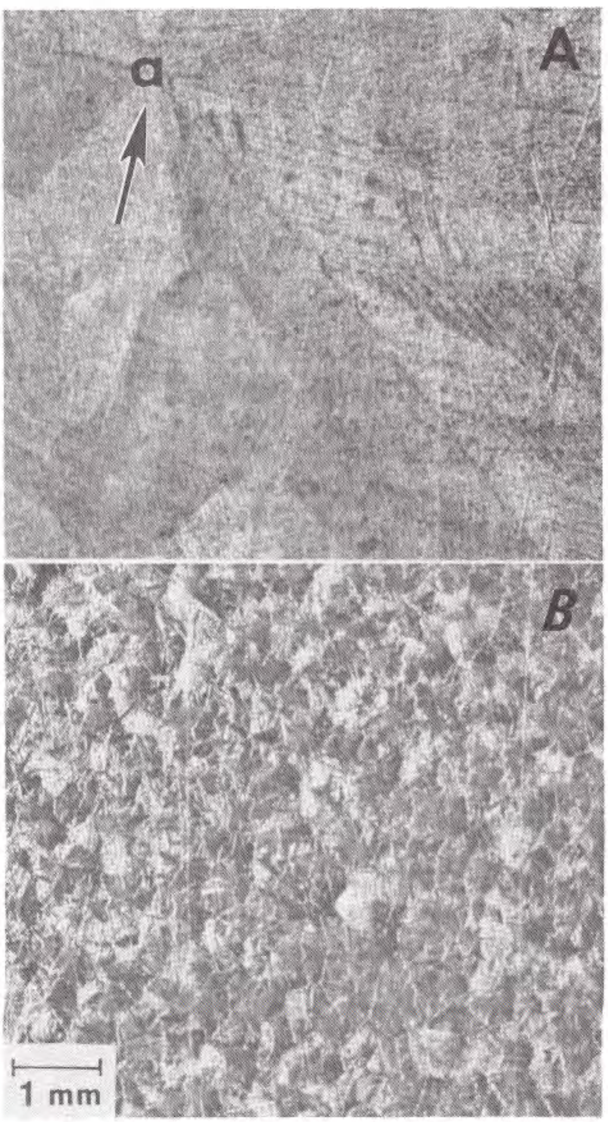

Fig. 1. Surface spangles in hot dip zinc coatings (A) coarse spangles, specimen *X*, (B) fine spangles, specimen *Z*. (Light macrographs).

Experimental Procedure

The three hot dip zinc coatings, identified as *X*, *Y*, and *Z*, chosen for this study represented a distribution in spangle sizes and crystallographic textures as summarized in Table 1. Coatings *X* and *Y* have large spangle sizes, but different texture. Coatings *Y* and *Z* have similar texture, but different spangle sizes. The x-ray and SEM analytical techniques used in this work are described elsewhere [5].

Results

Figure 1 shows the spangles in the large (*X*) and the small (*Z*) spangled coatings. The difference in spangle size is greater than an order of magnitude. A spangle on galvanized iron consists of many grains growing from several nuclei which are related to each other in orientation [6, 7]. Thus, each spangle is subdivided into spangle sectors, and each sector of the spangle represents an individual crystal. The spangle sectors are roughly triangular in shape and the span-

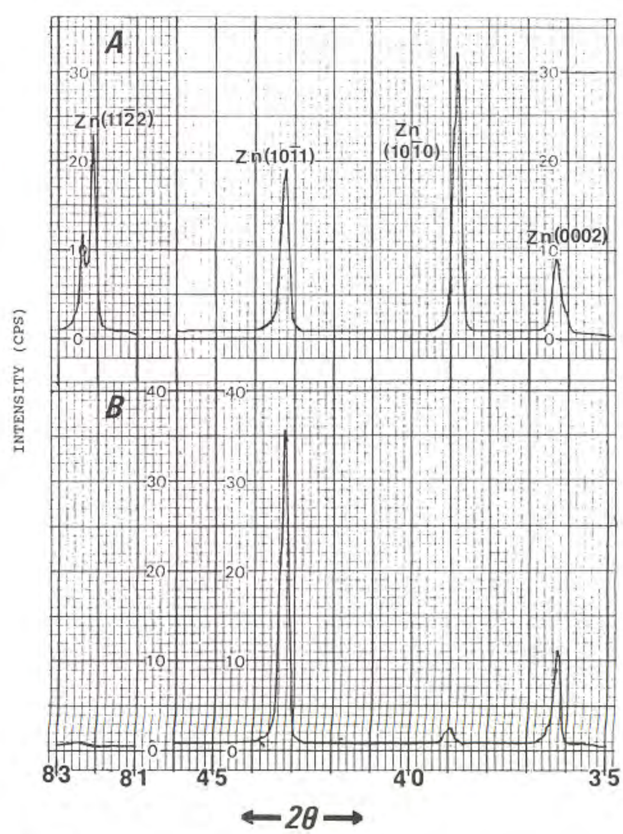

Fig. 2. X-ray diffraction profile from hot dip zinc coating, specimen *X*. Plots *A* and *B* show profiles from different locations on specimen *X*.

gle itself has a starlike appearance. This arrangement is shown in Figure 1(A), where a starlike pattern originates at point (a). The size of spangles can be controlled by proper additions of lead, tin and cadmium to molten zinc baths [8]. For example, a low Pb content in the bath promotes small spangle sizes or a spangle free appearance.

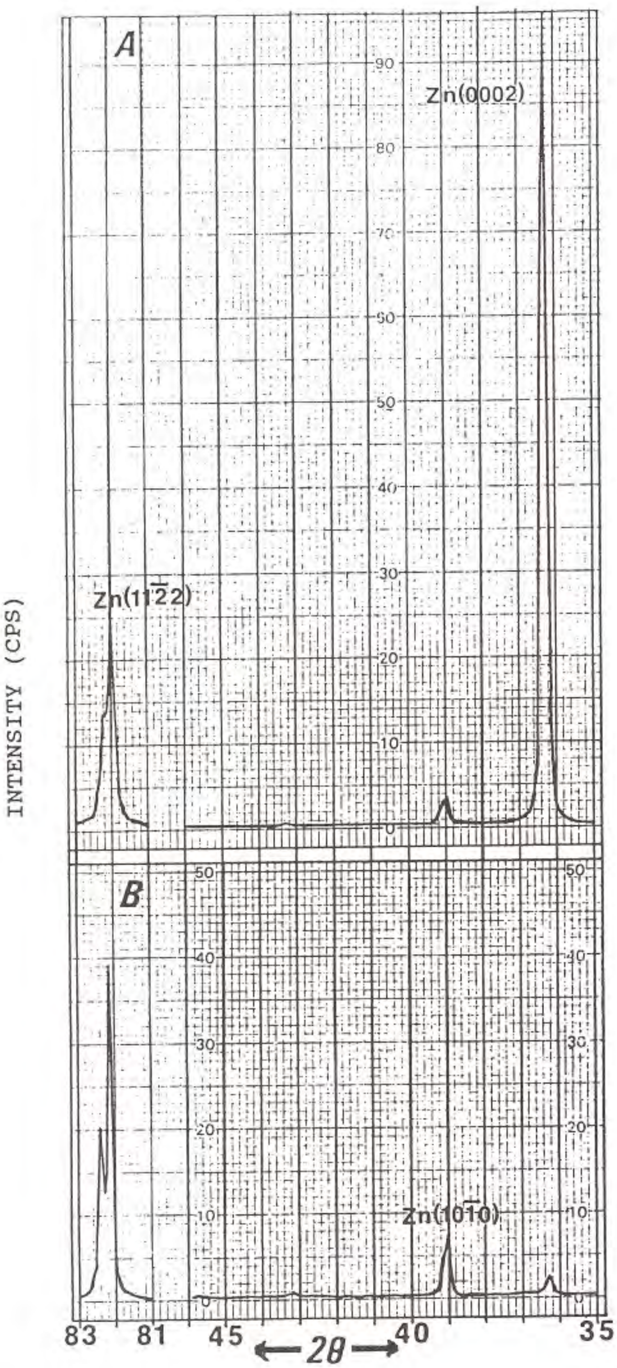

Fig. 3. X-ray diffraction profile from hot dip zinc coating, specimen *Y*. Plots A and B show profiles from different locations on specimen *Y*.

The x-ray diffraction patterns obtained on the three coatings are given in Figures 2 to 4. These figures show diffracted x-ray peak intensities plotted as a function of 2θ. In these plots, only planes parallel to the sample surface contribute to the diffracted intensities. In Figures 2 to 4, traces obtained from two different locations on a sample are presented. For each material, the pairs represent the maximum observed differences in the recorded diffraction patterns. For the materials with large spangles, *X* and

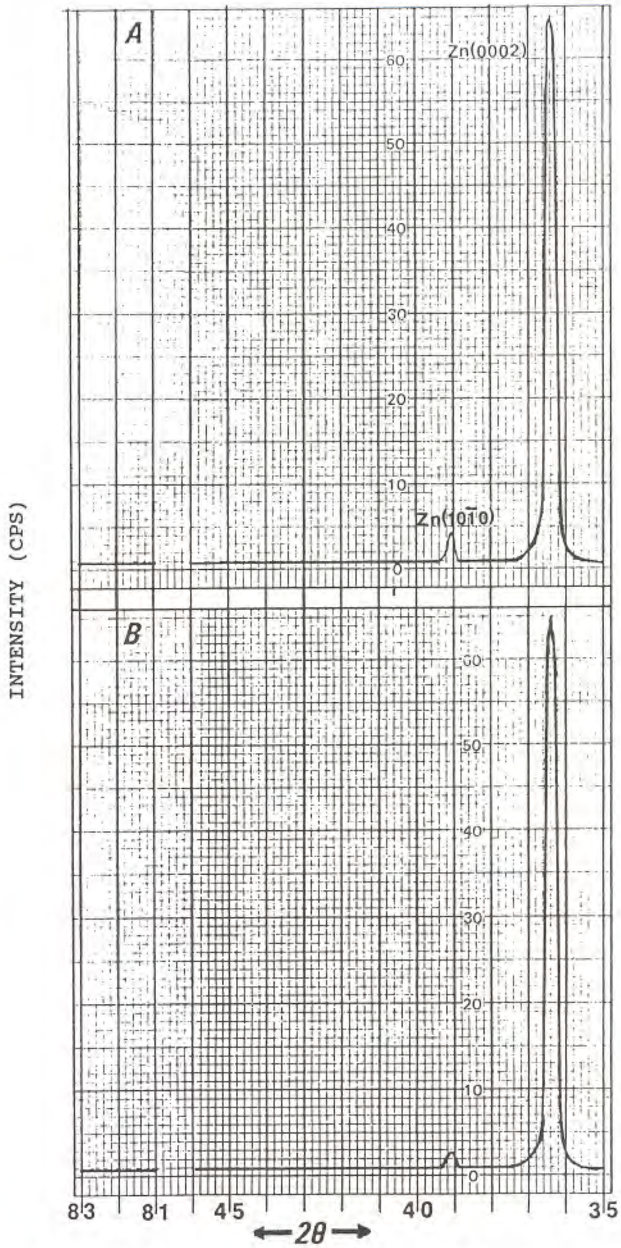

Fig. 4. X-ray diffraction profile from hot dip zinc coating, specimen *Z*. Plots A and B show profiles from different locations on specimen *Z*.

Y, the diffraction pattern varies significantly with location. In these materials, a relatively small number of spangles contribute to the diffracted intensity. Thus, the diffraction pattern is very sensitive to the crystallographic orientations of the few spangle sectors being analyzed. In a fine spangled material, a much higher number of spangles contribute to diffraction, and variations in peak intensities with specimen translation are minimal. Consistent with the latter observation, Figure 4 shows identical peak intensity ratios from different locations on the fine spangled material, *Z*.

In Figures 2 to 4 the Zn{0002} peak occurs at a 2θ value of 36.3 deg. Based on the intensity of the Zn{0002} peak relative to that of other peaks, specimen *Z* (Fig. 4) shows a strong and uniform basal plane texture, specimen *Y* (Fig. 3) shows a strong but nonuniform basal plane texture, and specimen *X* (Fig. 2) shows a lack of preferred basal plane orientation parallel to the coating surface.

A strong basal plane texture is unfavorable for slip and contributes to cracking during tensile deformation [5]. In the present case, the galvanized sheets were subjected to a complex roll forming operation which induced tensile strains. A schematic of the roll forming operation is shown in Figure 5(A) and the formed product is shown in Figure 5(B). Two zones subjected to high biaxial tensile strains are indicated in Figure 5(B). The cracking and the corrosion behavior of these regions are described below.

Figure 6 shows representative surface crack mor-

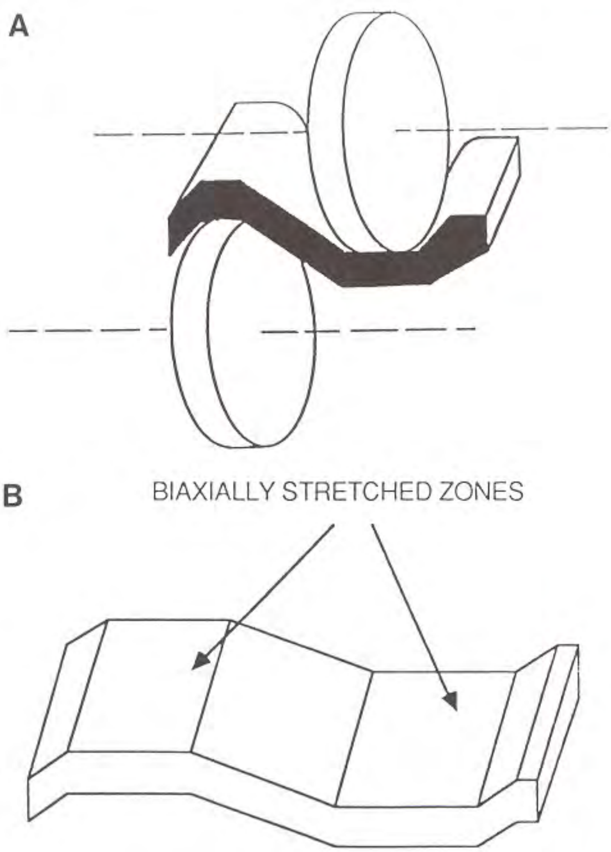

Fig. 5. Schematic diagrams of (A) the roll-forming operation and (B) the formed sheet with biaxially stretched zones indicated.

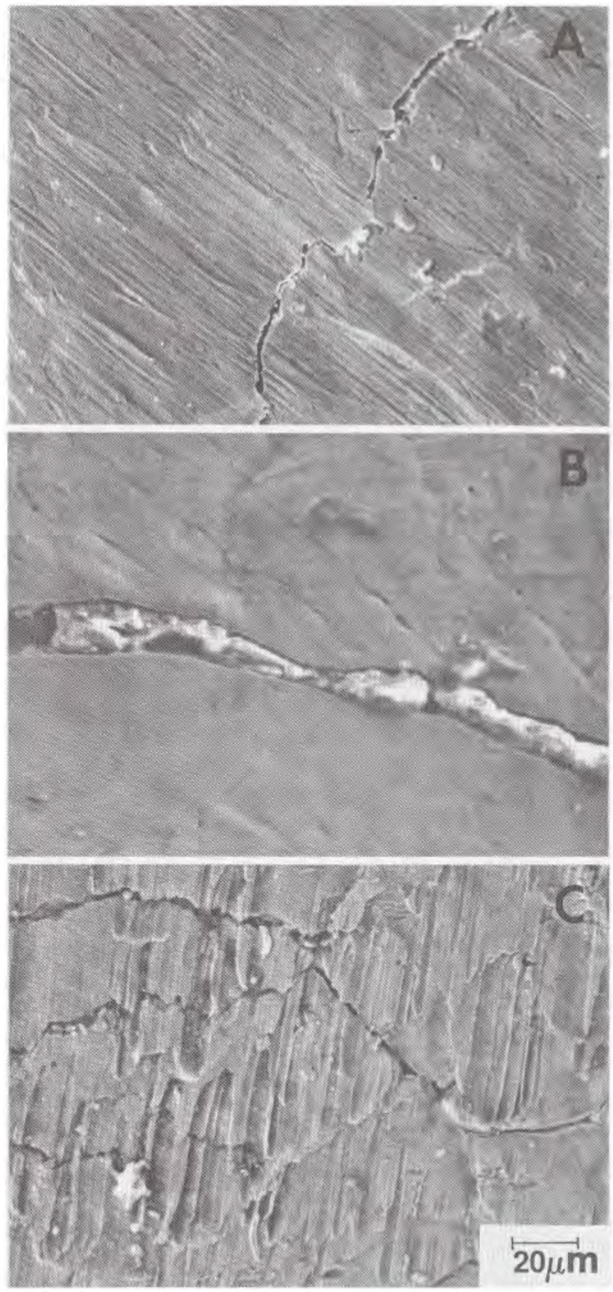

Fig. 6. Examples of crack morphologies in (A) specimen *X*, (B) specimen *Y*, and (C) specimen *Z*. (SEM micrographs.)

phologies from the three coatings. All three coatings exhibit cracking. Coating X with large spangle size and a low basal plane texture accommodates strain by a combination of plastic flow and cracking. Because most of the forming strain was accommodated by slip, the crack faces showed little separation. Material Y with a large spangle size and a dominant basal plane texture accommodated strain primarily by the development of large, wide cracks with limited associated plastic flow. As a result, galvanic corrosion was activated and the cracks filled with Zn-based corrosion products [Figure 6(B)]. Material Z with the most dominant basal plane texture, and the smallest spangle size, exhibited extensive fine cracking. Since the same amount of strain is accommodated by many cracks in material Z compared to the large spangled material Y, crack widths were smaller and the critical area of steel required to activate galvanic corrosion was not exposed.

Summary

The above results show variable deformation and fracture behavior of hot dip pure zinc coatings subjected to the same strain state. The differences in response to forming stem from the effects of crystallographic texture and the spangle size. Nonbasal plane textures and small spangle sizes are desirable features in hot dip zinc coatings in order to avoid wide forming cracks which initiate early occurrence of corrosion in formed parts.

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