Multiple cracking of galvannealed coating layer on steel substrates

S. Iwamoto[1], S. Ochiai[2] , H. Okuda[2], and T. Nakamura[1]
[1] Graduate School of Engineering, Kyoto University, Sakyo-ku, Kyoto 606-8501, Japan
[2] International Innovation Center, Kyoto University, Sakyo-ku, Kyoto 606-8501, Japan

ABSTRACT

The fracture behavior of the Fe-Zn intermetallic compound coating layer on ductile steel substrate sheets was studied experimentally and analytically. When tensile strain was applied, the brittle Fe-Zn intermetallic compound coating layer showed multiple cracking perpendicular to the tensile axis. The average crack spacing of the coating layer decreased with increasing applied strain. The crack spacing for a given strain was dependent on the coating thickness and species of the steel substrate. The calculation of the exerted stress of the coating layer with the finite element method revealed that, when the steel substrate deformed plastically and the crack spacing was narrow, the maximum tensile stress of the coating layer was approximately proportional to the crack spacing and tensile stress of substrate at the corresponding strain, and inversely proportional to the coating thickness. From the comparison of the measured crack spacing versus strain with the calculated one, the average strength of the coating layer was estimated to be around 250 MPa. From these results, an empirical equation was proposed, which can be used for rough prediction of the crack spacing as a function of applied strain for any substrate steels and thickness of the coating layer.

1. INTRODUCTION

Coating of metals with ceramic or intermetallic compound is useful in improvement of the wear resistance and in protection from the environmental attack, and is widely applied. For instance, hot-dip galvanized steel, having the coating layer of Fe-Zn intermetallic compounds on the surface of IF (interstitial free) steel is widely used in automotive industry [1]. As these materials are composed of brittle coating layer with low failure strain and ductile substrate with far higher failure strain, the coating layer exhibits multiple cracking perpendicular to the tensile direction when tensile stress is applied externally [1,2,3]. The aim of the present work is to investigate the influence of the species of the steel substrate and thickness of the coating layer on the multiple cracking behavior of the coating layer. For this aim, the fracture behavior of the coating layer was observed using two kinds of the specimens with different substrate and different thickness of the coating layer. Then the results were analyzed with the finite element method.

2. EXPERIMENTAL PROCEDURE

2.1 Specimens and tensile test

The used samples were the hot-dipped Fe-Zn intermetallic compound-coated IF (Interstitial Free) and SPCC (Steel Plate Cold Commercial) steels. The chemical compositions of the substrate IF and SPCC steels are listed in Table l. Hereafter, the IF and SPCC steel-based samples are noted as sample L and sample P, respectively. The steel plates were prepared by the heat-treatment at 773 K for 80 s of the hot-dipped galvanized steel. The coating layer was composed of thin ζ phase layer

Table 1. Chemical composition of the steel used as substrate (mass%).

	C	Si	Mn	P	S	Al	Ti
Sample L	0.002	0.008	0.1	0.01	0.006	0.024	0.051
Sample P	0.04	0.005	0.18	0.013	0.012	0.014	-

covered by very thin zinc η phase resulting from solidification, followed by thick δ_1 phase occupying approximately 80 % in volume of the coating layer and then a thin Γ_1 phase layer in contact to the substrate steel. The overall thickness of the coating layer was 10 and 5 μm for the IF and SPCC steels, respectively.

Tensile test was carried out at room temperature at a crosshead speed of 8.3×10^{-6} m/s for a gage length 50 mm using the specimen with a length 100 mm, width 10mm and thickness 0.8 mm. The crack spacing of the coating layer at 4, 10, 15 and 20 % applied strain was measured with the scanning electron microscope (SEM). The strain of the specimens was measured with the non-contact laser extensometer (Shimazu DVE-200).

2.2 Finite element analysis

The morphology of the specimen with multiply cracked Fe-Zn intermetallic compound coating layer is schematically shown in Fig.1 (a) where L is the crack spacing and T is the thickness of the coating layer. In the finite element analysis to calculate the stress distribution, a plane-strain model was used, in which the region ABFE was taken up as the representative. The longitudinal distance y was taken from the center plane: y = 0 at AB, y = 400 μm at CD and y= 400 μm +T at EF. The horizontal distance x was defined to be zero, at the broken end, L/2 at the middle, and L at the another broken end as shown in Fig.1.

An example of the finite element mesh of the plane-symmetric model and the boundary conditions employed in the present analysis are shown in Fig.1 (b). The displacements of the cross-sections ACE and AB were taken to be zero. Common compulsory tensile displacement

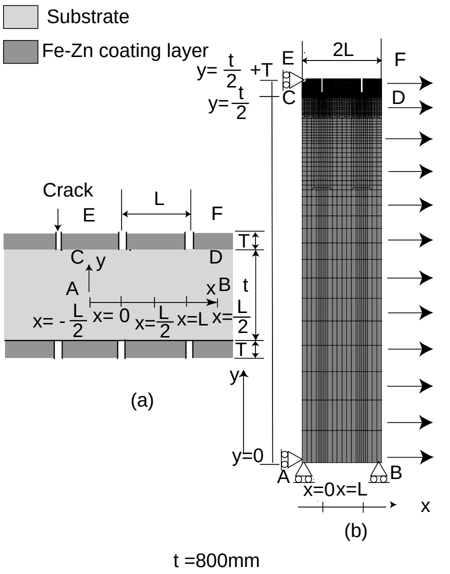

Fig.1 FEM-mesh and boundary condition of the GA steel for stress analysis.

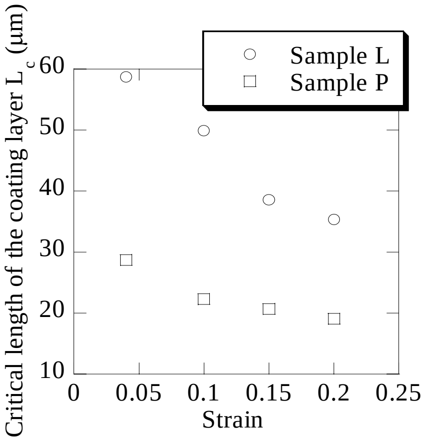

Fig.2 Relation between the measured value of the critical length of the coating layer and nominal strain.

was given for the cross-section BDF in the x-direction.

For analysis of the stress distribution, the crack spacing L = 10, 20, 30, 40 and 80 μm and the thickness of the coating layer T = 2, 5, 10 and 15 μm were used. As mentioned above, the present specimens were heated for formation of the intermetalic compounds at 773 K and cooled down to room temperature. Therefore the temperature change ΔT = -475 K was input. The stress of the coating layer in the x-direction, σ_x, was calculated for the applied tensile strain = 10, 20 and 30%.

The analysis was carried out with the commercial finite element code MARC/Mentat2001. The Young's modulus, shear modulus, Poisson's ratio and coefficient of linear expansion of the steel substrate were taken to be 210GPa [4], 81GPa, 0.30 [4] and $2.2\text{x}10^{-5}$ /K [5,6] respectively [7] and those of the coating layer to be 140GPa [4], 54GPa, 0.30 [4] and $1.1\text{x}10^{-5}$ /K [5,6] respectively from the reported value for δ_1 Phase that occupies 80% in volume fraction of the coating layer. The true stress (σ) - true plastic strain (ε_p) curve of the present steel substrate was expressed by,

$$\sigma=130+400\varepsilon_p^{0.38} \quad \text{(Sample L)} \quad (1)$$
$$\sigma=280+320(\varepsilon_p-0.02)^{0.51} \quad \text{(Sample P)} \quad (2)$$

The yielding condition for the steel substrate was given by the von Mises criterion.

3. RESULTS

3.1 Results of tensile test

The Fe-Zn intermetallic coating layer exhibited multiple cracking when tensile stress was applied externally. As shown later in 3.2, the stress exerted on the coating layer was highest at the middle (x = L/2). When the cracking of the coating layer occurred at x = L/2, the relation between the critical length of the coating layer L_c (= the necessary length for the coating layer to be cracked) and the average crack spacing L_{ave} is given by [8],

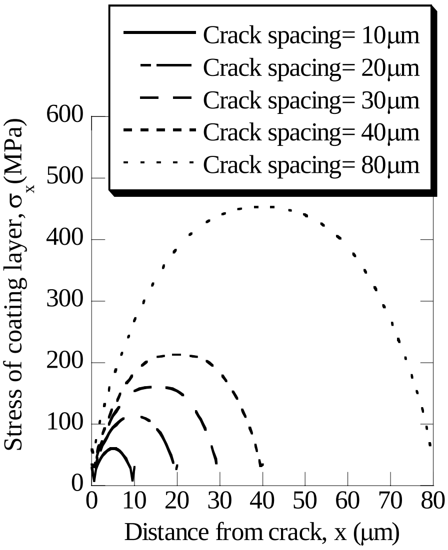

Fig.3 Tensile stress distribution in the coating layer at the nominal strain =10%, for the crack spacing = 10μm, 20μm, 30μm, 40μm and 80μm. (Sample L)

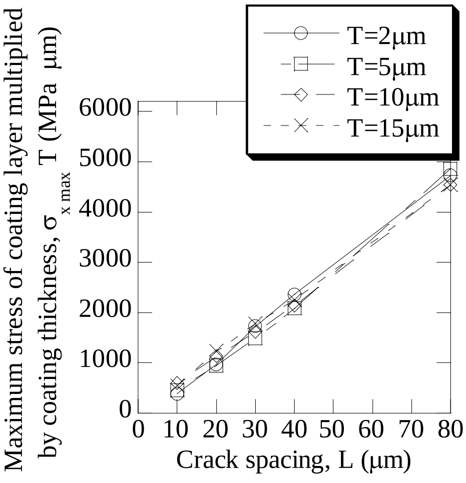

Fig.4 Relation between the maximum tensile stress of coating layer multiplied by coating thickness and crack spacing, at the nominal strain = 10%, for the coating thickness = 2μm, 5μm, 10μm and 15μm. (Sample L)

$$L_c = \frac{4}{3} L_{ave} \qquad (3)$$

Substituting the measured L_{ave} value into eqn(3), we had the critical length of the coating layer L_c. The change of L_c with increasing applied strain is presented in Fig.2. Evidently, the critical length decreased with increasing strain.

3.2 Finite element analysis

First, the tensile stress at the nominal strain = 10, 20 and 30% of the coating layer were calculated for L = 10, 20, 30, 40 and 80 μm and for T = 10 μm (Sample L) and 5 μm (Sample P). In the following parts, the tensile stress σ_x in the x-direction, averaged in the y-direction, of the coating layer, is presented.

Figure 3 shows the variations of thus calculated tensile stress σ_x in the x-direction of the coating layer with distance from the crack x at the applied nominal strain of 10% (Sample L). Evidently, the σ_x is highest ($\sigma_{x\,max}$) at the middle point x = L/2. It is noted that the exerted stress on the coating layer increases with increasing crack spacing. This suggests that the longer segment tends to be cracked.

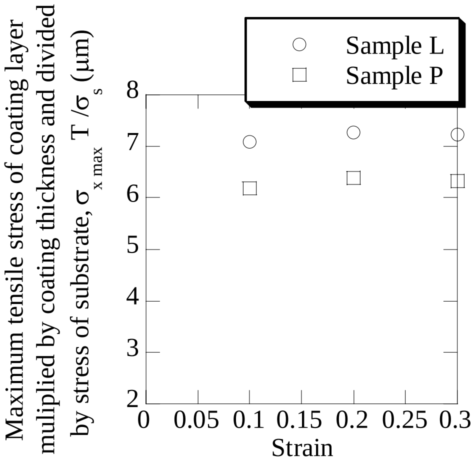

Fig.5 Relation between the maximum tensile stress of coating layer multiplied by coating thickness and divided by stress of substrate and nominal strain (Sample L, coating thickness = 10μm, and Sample P, coating thickness = 5μm)

The calculation results showed that the thinner and the longer the coating layer, the higher becomes $\sigma_{x\,max}$. Figure 4 shows the relation between the maximum tensile stress $\sigma_{x\,max}$ multiplied by the coating layer thickness T and crack spacing L at the applied strain = 10% (Sample L). The $\sigma_{x\,max}$ T is nearly proportional to L.

Figure 5 shows the relation between the $\sigma_{x\,max}$ T /σ_s and applied strain for a given crack spacing L = 40 μm, where σ_s is the tensile stress of the substrate at the corresponding strain. Figure 5 suggests that the $\sigma_{x\,max}$ T is proportional to σ_s at any strain, to a first approximation, within the present calculation.

For wide variety of L, T, and strain, similar calculation was carried out. The result indicated that $\sigma_{x\,max}$ T is nearly proportional to L and σ_s, namely $\sigma_{x\,max}/\sigma_s$ is nearly proportional to L/T at any strain as shown in Fig.6. These results suggest that the following equation is hold as a first approximation.

$$\frac{\sigma_{x\ max}}{\sigma_s} = C\frac{L}{T} \qquad C=\text{const.} \quad (4)$$

From the slope in Fig.6, the constant C was estimated to be around 0.18 commonly to IF (Sample L) and SPCC (Sample P) substrates, despite the difference in mechanical property between substrates (yield stress 130 MPa (Sample L) and 280 MPa (Sample P), tensile strength 280 MPa (Sample L) and 340 MPa (Sample P), and strain hardening coefficient 0.38 (Sample L);eqn (1) and 0.51 (Sample P) ;eqn (2)).

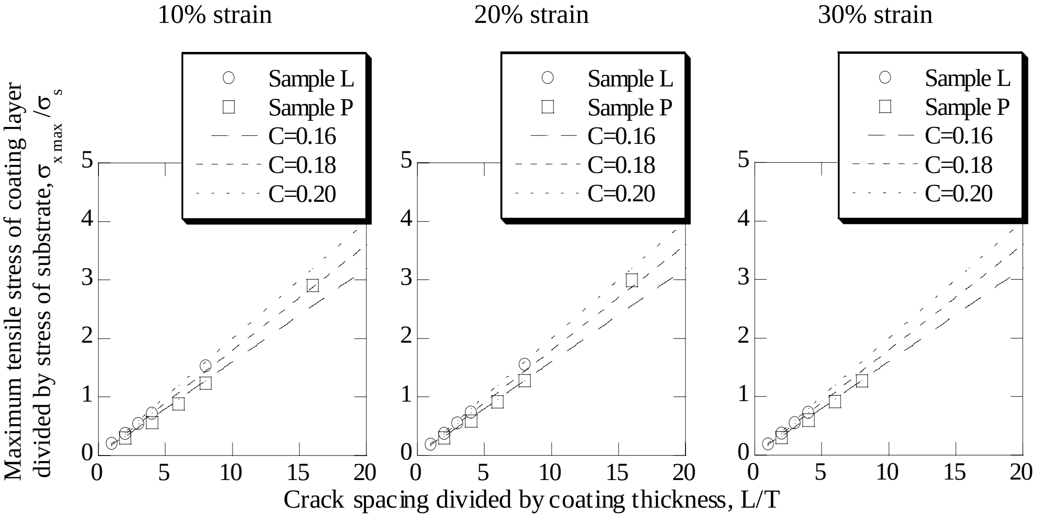

Fig.6 Relation between the maximum tensile stress of coating layer divided by stress of substrate and crack spacing divided by coating thickness for applied strain = 10, 20 and 30%.

Noting the strength of the coating layer σ_c, substituting $\sigma_{x\,max} = \sigma_c$ and $L = L_c$ in to eqn (4), the critical length of the coating layer L_c is given by,

$$L_c = \frac{T}{C}\left(\frac{\sigma_c}{\sigma_s}\right) \qquad (5)$$

Substituting the parameters C = 0.18, T = 10 μm (Sample L) and 5 μm (Sample P), and σ_s given by eqns (1) (Sample L) and (2) (Sample P) as a function of strain, the variation of L_c as a function of strain can be calculated if the strength of the coating layer σ_c is known. In the present work, as the σ_c-value was unknown, various values of σ_c were input into eqn (5) and the fit value of σ_c to the measured variation of critical length were sought. Examples for σ_c = 200, 250 and 300 MPa are presented in Fig.7. It was found that σ_c = 250 MPa could describe the experimental result for both IF and SPCC substrate specimens. The constant C and the average strength of the coating layer σ_c were almost independent from the species of the substrate steel. It is noted that, if the values of C and σ_c estimated to be around 0.18 and 250 MPa, respectively, are common for any substrate steel, we can, hereafter, predict the L_c as a function of

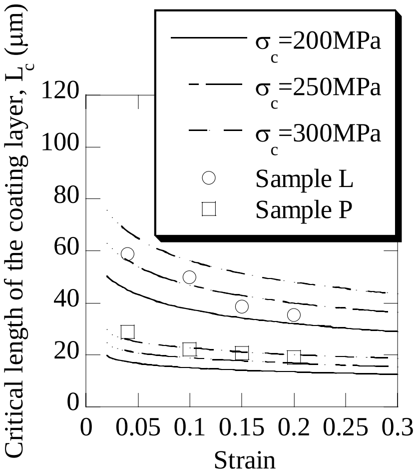

Fig.7 Relation between the critical length of the coating layer and normal strain, for the strength of coating = 200, 250 and 300 MPa (Sample L, coating thickness = 10 μm and Sample P, coating thickness = 5 μm)

applied strain by substituting T and σ_s into eqn(5) for any substrate steels. This approach is not rigid but is very simple and convenient for rough prediction.

4. CONCLUSIONS

The fracture behavior of the Fe-Zn intermetallic compound coating layer on ductile steel substrate sheets was studied. The main results are summarized as follows.

(1) Based on the finite element analysis, the following equation was derived,

$$\frac{\sigma_{x\ max}}{\sigma_s} = C\frac{L}{T} \qquad C \approx 0.18$$

(2) Application of equation in (1) to the experimental results revealed that the average strength of coating layer σ_c on IF and SPCC substrate steels was around 250 MPa.

(3) The critical length of the coating layer L_c at the strain was expressed as,

$$L_c = \frac{T}{C}\left(\frac{\sigma_c}{\sigma_s}\right)$$

With this equation, as the σ_c-value is now known (250 MPa), the change of critical length of the coating layer with applied strain could be predicted to a first approximation for any species of the substrate steel only by substituting the flow stress after corresponding strain of the substrate and thickness of the coating layer.

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