Influence of the Crack Spacing in the Coating Layer on the Progress of Interfacial Debonding in Galvannealed Steel Pulled in Tension

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The coefficient of thermal expansion of the coating layer of the hot-dipped galvannealed steels is higher than that of the substrate steel. Accordingly, the coating layer shows multiple cracking during cooling due to the thermally induced stress. When tensile stress is applied externally on the coated steels, the coating layer exhibits further multiple cracking perpendicular to the tensile direction. As a result, the coating layer is multiply-cracked both in tensile and sample width directions. Under such existing cracks, the coating layer is spalled due to the interfacial debonding induced by the buckling of the coating layer in the sample width direction. In the present work, the influences of the crack spacing in the tensile direction and that in the sample width direction on the spalling process of the coating layer were studied with the finite element stress analysis. The results of analysis showed that (a) the larger the crack spacing of the coating layer in the tensile direction, the more the interfacial debonding and (b) the crack spacing in the tensile direction affects especially on the initial spalling behavior; the larger the spacing, the more the spalling is enhanced. On the other hand, the crack spacing in the sample width direction affects only slightly on the initial spalling behavior, while the larger the spacing, the larger becomes the debonding area in the later stage.

KEY WORDS: finite element analysis; galvannealed steel; coating; cracking; spalling; interface.

1. Introduction

The GA (galvannealed) steels, consisting of Fe–Zn intermetallic coating layer and substrate steel, are widely used as architectural and car-body materials due to their high corrosion resistance and weldability.1,2) 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,3–12) followed by spalling, when tensile stress is applied externally. In our former work, the following spalling process, as schematically shown in Fig. 1,17) was suggested from the observation and the numerical analysis. The coating layer exhibits multiple cracking both under thermally induced residual stress and externally applied stress (Figs. 1(a) and 1(b)). With increasing tensile strain, the compressive stress in the sample width direction increases in the coating layer (Fig. 1(c)). Then the coating layer is bent (Fig. 1(d)) according to which, the upper side is cracked due to the tensile stress. Such a crack enhances the buckling of the coating layer (Fig. 1(e)). In the progress of the buckling, tensile stress is exerted at the interface between the coating layer and substrate, due to which interfacial debonding occurs. Finally the debonded coating layer is spalled (Fig. 1(f)).17)

Figure 2 shows the SEM image of the multiple cracking of the GA coating layer in the sample used in this work under applied tensile strain. As shown in Fig. 2, the coating layer was cracked not only perpendicular to the tensile direction but also parallel to the tensile direction. Cracks induced perpendicularly to the tensile direction were caused by the multiple cracking, as mentioned above. On the other hand, the cracks induced parallel to the tensile direction (namely the cracks in the sample width direction) were caused by the thermally induced residual stress.13–16,19–21) However, the influences of the crack spacing in the tensile direction and that in the sample width direction have not been clarified until now, despite the importance to clarify the spalling behavior. In our recent study, concerning the fracture of GA coating layer with high tensile strength steel substrates, it was newly suggested that the interfacial debonding could be reduced through the enhancement of multiple cracking.22) In the present work, it was attempted to reveal the influences of the crack spacing in both tensile and sample width directions on the spalling behavior of the coating layer with the finite element stress analysis.

2. Finite Element Analysis

3-dimensional models for analysis of interfacial debonding of the coating layer were prepared as follows. The morphology of the specimen with multiple cracked Fe–Zn in-
intermetallic compound coating layer is schematically shown in Fig. 3(a) where $L$ is the crack spacing in the tensile direction, $W$ is the crack spacing in the width direction and $T$ is the thickness of the coating layer. The finite element mesh is dependent on the value of $L$ and $W$. An example of the finite element mesh of the model employed in the present analysis is shown in Fig. 3(b). As indicated in Fig. 3(a), the longitudinal distance $x$ was taken to be zero at the middle, and to be $L/2$ at the crack. The distance $y$ in the sample width direction was taken to be zero at the crack, to be $W/2$ at the middle, and to be $W$ at another crack. The vertical distance $z$ was taken to be zero at the middle of substrate in the thickness direction. As the thickness of the substrate $t$ was 800 $\mu$m, the distance $z$ of the coating layer/substrate interface was taken to be 400 $\mu$m ($=t/2$), and the distance $z$ at the surface of the coating layer was taken to be 400 $\mu$m $+T$ ($=10 \mu$m in the present sample).

In the early stage of multiple cracking, the crack spacing is large. When the maximum stress exerted on the coating layer is larger than the strength of the coating layer, the long coating layer is cracked. The crack spacing, at which the strength is equal to the maximum stress on the coating layer, has been named as the critical length $L_c$. Noting the crack spacing as $L_i$, cracking occurs more if $L_i > L_c$ but stops if $L_i < L_c$ under a given applied strain. In the case of $L_i = L_c$, the crack spacing becomes $L_c/2$. In the case where $L_i$ is just below $L_c$, no more cracking occurs and the crack spacing remains $L_c$. Averaging the lower ($=L_c/2$) and upper limits ($=L_c$), the average crack spacing $L_{ave}$ for applied strain is, to a first approximation, given by,

$$L_{ave} = (L_c + L_c/2)/2 = (3/4)L_c$$

The average crack spacing $L_{ave}$ was measured as the distance between the cracks. More than 100 crack spacing values were measured at each applied strain. In the present analysis, the crack spacing $L$ in the $x$-direction (tensile direction) was taken to be 40 $\mu$m, and that $W$ in the $y$-direction was 800 $\mu$m, and $T$ in the $z$-direction was 10 $\mu$m. The thickness of the substrate $t$ was 800 $\mu$m, the distance $z$ of the coating layer/substrate interface was taken to be 400 $\mu$m ($=t/2$), and the distance $z$ at the surface of the coating layer was taken to be 400 $\mu$m $+T$ ($=10 \mu$m in the present sample).

![Fig. 1. Schematic representation of the spalling process of the coating layer.](image1)

![Fig. 2. SEM image of the multiple cracking of the coating layer.](image2)

![Fig. 3. Modeling for finite element analysis of interfacial debonding. (a) Schematic representation of the morphology of the specimen with multiple cracked Fe–Zn intermetallic compound coating layer. (b) An example of the finite element mesh of the model.](image3)
Debonding distance

Fig. 4. Calculated distributions of the interfacial debonding distance from substrate to the coating layer for $L=40 \mu m$ and $W=80 \mu m$ at (a) 5%, (b) 8% and (c) 10% tensile strain.

3. Results and Discussion

3.1. Initial Spalling Process Calculated by the Finite Element Method

The finite element analysis was carried out for the crack spacing $(L/\mu m, W/\mu m)=(20, 80)$, $(40, 80)$, $(60, 80)$ and $(40, 40)$, $(40, 60)$, $(40, 80)$. As the calculation results using these crack spacing-values had similar features in the initial spalling process of the coating layer, the result for $(L/\mu m, W/\mu m)=(40, 80)$ is representatively taken up in this part.

Figure 4 shows the calculated distributions of the debonding distance from the substrate to coating layer at (a) 5%, (b) 8% and (c) 10% tensile strain.

As shown in Fig. 4, the spalling process of the present analysis could be divided into three stages. In the stage I (3–5% tensile strain), as represented in Fig. 4(a), interfacial debonding starts at the edge of the coating (at the position of $x=L/2$ and $y=W/2$). In the stage II (6–8% tensile strain), as represented in Fig. 4(b), interfacial debonding reaches the center of the coating (at the position $x=0$ and $y=W/2$). In the stage III (9–15% tensile strain), as represented by Fig. 4(c), the coating is largely debonded and the debonding distance increases.

Fig. 5. Schematic drawing of the analyzed spalling process of the coating layer.
brittle coating (Poisson’s ratio 0.3) and the plastically deforming substrate (0.5). As a result, the coating layer exhibits buckling.

Figure 6 shows the progress of the debonded area of coat/substrate interface with increasing applied strain. The debonded part of the coating is shown in black color in Fig. 6. As shown in Fig. 6, the debonded area progressively increases from the edge \((x, y) = (L/2, W/2)\), and rapidly progresses in the \(y\) direction after the debonding at the center \((x, y) = (0, W/2)\).

Figure 7 shows the change of the occupancy of the debonded area \((=\text{ratio of the debonded area (shown in block color in Fig. 6) to the whole area of the interface)}) with applied tensile strain. The strains indicated with (a), (b) and (c) correspond to the strains shown in Fig. 4(a), 4(b) and 4(c), respectively. As shown in Fig. 7, each stage mentioned above has specific features. In the stage I, interfacial debonding starts but the occupancy of the debonded area varies only slightly. On the other hand, the occupancy of the debonded area increases largely in the stage II. In the stage III, the occupancy of the debonded area approaches unity.

3.2. Influence of Crack Spacing on the Spalling Behavior of the Coating Layer

In Sec. 3.1, the result for \((L/\mu m, W/\mu m) = (40, 80)\) was representatively taken up to show the feature of the spalling process qualitatively. In this part, the influence of crack spacing on the spalling behavior of the coating layer is discussed quantitatively by comparing the calculation results for the different crack spacing \((L/\mu m, W/\mu m) = (20, 80), (40, 80), (60, 80)\) and \((40, 40), (40, 60), (40, 80)\).

Figures 8 and 9 show the calculated distributions of the debonding distance from the substrate to coating layer at 10% tensile strain for the crack spacing \((L/\mu m, W/\mu m) = (a) (20, 80), (b) (40, 80)\) and \(c) (60, 80)\), and for the crack spacing \((L/\mu m, W/\mu m) = (a) (40, 40), (b) (40, 60)\) and \(c) (40, 80)\), respectively.

The following features are read from Figs. 8 and 9.

(i) The debonding distance of the coating layer decreases with decreasing crack spacing \(L\) in the tensile direction and also \(W\) in the sample width direction.

(ii) Under a given crack spacing \(W\) in the sample width direction (Fig. 8), the debonding progresses for both small (a) and large (c) crack spacing \(L\) in the tensile direction, while the coating layer is curved more in the tensile direction for the larger crack spacing \(L\).

(iii) Under a given crack spacing \(L\) in the tensile direction (Fig. 9), the debonding distance is very small for small crack spacing \(W\) but is very large for large \(W\). The influence of the crack spacing \(W\) on the interfacial debonding is dominant in comparison with that of \(L\) under a given crack spacing \(W\).

Figures 10 and 11 show the progress of the debonded area of coat/substrate interface with increasing applied strain for the crack spacing \((L/\mu m, W/\mu m) = (a) (20, 80), (b) (40, 80)\) and \(c) (60, 80)\), and for the crack spacing \((L/\mu m, W/\mu m) = (a) (40, 40), (b) (40, 60)\) and \(c) (40, 80)\), respectively. Figure 12 shows the change of the occupancy of the
Fig. 8. Calculated distributions of the interfacial debonding distance from substrate to the coating layer at 10% tensile strain for the crack spacing \((L/\mu m, W/\mu m)\) = (a) (20, 80), (b) (40, 80) and (c) (60, 80), respectively.

Fig. 9. Calculated distributions of the interfacial debonding distance from substrate to the coating layer at 10% tensile strain for the crack spacing \((L/\mu m, W/\mu m)\) = (a) (40, 40), (b) (40, 60) and (c) (40, 80), respectively.

Fig. 10. Progress of the debonded area of coat/substrate interface with increasing applied strain for the crack spacing \((L/\mu m, W/\mu m)\) = (a) (20, 80), (b) (40, 80) and (c) (60, 80).
debonded area with applied tensile strain (a) for the crack spacing \((L/\mu m, W/\mu m)\) = (20, 80), (40, 80) and (60, 80) and (b) for the crack spacing \((L/\mu m, W/\mu m)\) = (40, 40), (40, 60) and (40, 80).

As shown in Figs. 10 and 12(a), the crack spacing \(L\) in the tensile direction strongly affects on the early stage of spalling (stage I mentioned in Sec. 3.1) but affects only slightly on the later stages II and III. In the case of \((L/\mu m, W/\mu m)\) = (20, 80) where the crack spacing \(L\) in the tensile direction is very small, the stage I was very narrow, followed subsequently by the stage II. On the other hand, in the case \((L/\mu m, W/\mu m)\) = (60, 80) where the crack spacing \(L\) is large, the strain at which interfacial debonding starts become low and the occupancy of the debonded area became high in the stage I. This means that the crack spacing \(L\) in the tensile direction affects dominantly on the initial spalling behavior.

On the other hand, as shown in Figs. 11 and 12(b), the crack spacing \(W\) in the sample width direction affects strongly on the transition from the stage I to II. In the case
of \((L/\mu m, W/\mu m)=(40, 40)\), the spalling process remained in the stage I up to the applied strain 15%. In the case of \((L/\mu m, W/\mu m)=(40, 60)\), the occupancy of the debonded area increased slightly but the situation was the same as that in the case of \((L/\mu m, W/\mu m)=(40, 40)\). When the crack spacing \(W\) in the sample width direction was large as in the case of \((L/\mu m, W/\mu m)=(40, 80)\), all stages I, II and III appeared. In this way, the crack spacing \(W\) in the sample width direction gives dominant influence on the transition from the stage I to II.

Figures 13 and 14 show the changes of the debonding distance at \((x, y) = (a) (L/2, W/2)\) and \((b) (0, W/2)\) with applied tensile strain. The position \((x, y) = (L/2, W/2)\) corresponds to the cracked edge of the coating, and the position \((x, y) = (0, W/2)\) corresponds to the center of the coating, as indicated in Figs. 13 and 14. At the position \((x, y) = (L/2, W/2)\), the debonding initiates and the debonding distance is maximum at any applied strain, as has been shown in Figs. 8 and 9. The debonding front in the \(x\) direction (tensile direction) moves from the edge \((x=L/2)\) to the center \((x=0)\) with increasing applied tensile strain. The calculation results at \((x, y) = (a) (L/2, W/2)\) and \((b) (0, W/2)\) for the crack spacing \((L/\mu m, W/\mu m)=(20, 80), (40, 80), (60, 80)\) in Fig. 13 show the following features for the influence of the crack spacing \(L\) in the tensile direction on the debonding process.

As shown in Fig. 13(a), the larger is the crack spacing \(L\), the larger becomes the maximum debonding distance at \((x, y) = (L/2, W/2)\). On the other hand, as shown in Fig. 13(b), the debonding behavior at \((x, y) = (0, W/2)\) in the early stage at around 7–9% strain is almost same for all crack spacing \(L\) and the debonding distance at \((x, y) = (0, W/2)\) becomes slightly small with increasing crack spacing \(L\) in the later stage. Such a feature is accounted for as...
follows. The larger the crack spacing \(L\), the higher becomes the interfacial stress to cause debonding at \((x, y) = (L/2, W/2)\). Accordingly, in the early stage of debonding (stage I), the debonding is enhanced for large \(L\). As shown in Fig. 4, the curvature in the \(x\) direction (tensile direction) is small up to initiation of deboning at \((x, y) = (L/2, W/2)\) at 5\% strain. Once debonding occurs, the coating layer is curved more in the tensile direction. The curvature of the debonded region of the coating layer is large for the larger crack spacing \(L\) (Fig. 8). This suggests that, once the debonding occurs at \((x, y) = (0, W/2)\), the debonding does not progress further until the curvature becomes large enough to generate the critical stress to cause debonding. Accordingly, high strain is needed to cause further debonding. As a result, the debonding distance at \((x, y) = (0, W/2)\) in stage II becomes slightly small with increasing crack spacing \(L\). In this way, it was revealed that the crack spacing in the tensile direction affects especially on the initial spalling behavior; the larger the spacing, the more the spalling is enhanced in the early stage of debonding but not in the later stage.

The calculation result of the debonding distance at \((x, y) = (a, L/2, W/2)\) and \((0, W/2)\) for the crack spacing \((L/\mu m, W/\mu m) = (40, 40), (40, 60), (40, 80)\) is shown in Fig. 14. As shown in Fig. 14(a), the larger the crack spacing \(W\), the larger becomes the maximum debonding distance of the coating. As shown in Fig. 14(b), the debonding didn’t occur at \((x, y) = (0, W/2)\) for the crack spacing \((L/\mu m, W/\mu m) = (40, 40)\) and \((40, 60)\) even at 15\% strain within the present calculation condition, while debonding at \((x, y) = (L/2, W/2)\) had occurred at around 5\% strain (Fig. 14(a)). This means that the stage II didn’t start in the case \((L/\mu m, W/\mu m) = (40, 40)\) and \((40, 60)\). On the contrary, for large crack spacing \(W\), the debonding progressed extensively in the whole applied strain range investigated.

From the present work, the influence of the crack spacing on the interfacial debonding was revealed with the finite element analysis. The results suggest that, to suppress the spalling of the coating layer, the crack spacing in the tensile direction should be short to retard the initiation of the debonding and the crack spacing in the sample width direction should be short, too, to retard the progress of the interfacial debonding.

In our former work,\(^{15, 22}\) it has been shown that, when (i) the coating is thin and (ii) the substrate is hard, the crack spacing becomes small, which will suppress the interfacial debonding, if the tensile strength of the coating layer and interfacial bonding strength are retained on the level of those for the low strength steel.

4. Conclusions

(1) The spalling process could be divided into three stages. In the stage I, interfacial debonding starts at the cracked edge of the coating (the position \(x = L/2\) and \(y = W/2\)). In the stage II, interfacial debonding reaches the center of the coating (the position \(x = 0\) and \(y = W/2\)). In the stage III where the debonding front has passed the center, the coating is largely debonded and the debonding distance increases.

(2) The debonding distance of the coating layer decreases with decreasing the crack spacing both in the tensile direction \(L\) and the sample width direction \(W\). The crack spacing \(L\) in the tensile direction affects especially on the stage I behavior. The crack spacing \(W\) in the sample width direction affects especially on the transition from the stage I to the stage II.

(3) The present results suggest that, in order to suppress the interfacial debonding, the crack spacing in the tensile direction should be short to retard the initial debonding, and the crack spacing in the sample width direction should be short, too, to retard the progress of the interfacial debonding.

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