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Characteristics of Out-of-Plane Deformation and Residual Stress Generated by Fillet Welding †

You Chul KIM*, Kyong Ho CHANG ** and Kohsuke HORIKAWA***

Abstract

Longitudinal bending deformation was largely influenced by the welding sequence. Its magnitude was the smallest in the case when welding was continuously performed from one side to the other side. It was not so greatly influenced by changing of the welding speed in actual operation or the welding heat input. Angular distortion was largely influenced by the welding sequence, changing of the welding speed or the welding heat input. When welding was continuously performed as above mentioned, its magnitude was the smallest. But, it was different for left and right sides. If the welding speed becomes fast, angular distortion tends to be large and to converge to a certain limit. Attention should be paid to angular distortion which was found to be large when it was estimated ignoring effect of the moving heat source. Angular distortion tended to be large until the relative heat input for the flange thickness reached a certain value. Then, when the welding heat input exceeded this certain value, it conversely became small. Generated residual stress σ_x (component of weld line direction) was largely influenced by the welding sequence. Residual stress, σ_x, became large when the welding speed became fast or the welding heat input became large.

KEY WORDS: (Fillet welding) (Welding deformation) (Residual stress) (Out-of-plane deformation) (Longitudinal bending deformation) (Angular distortion) (Welding sequence) (Welding speed) (Heat input) (FEM)

1. Introduction

The characteristics of out-of-plane deformation in fillet welding and its production mechanisms were investigated using by an instantaneous heat source model ignoring effect of the moving heat source to construct a system for the prediction, control or prevention of out-of-plane deformation and residual stress generated in fillet welding. It was found[1)] that the shape of longitudinal bending deformation was determined by the relative positions of the neutral axis for the cross section of the object in fillet welding and the heat source. That is, when the heat source exists above the neutral axis, the shape becomes concave, and when the heat source exists below the neutral axis, the shape becomes convex. However, even if the position of the neutral axis and the position of the welding heat source coincided, a small convex longitudinal bending deformation was produced because the central position of the welding heat source and the position of the neutral axis did not coincide as the heat diffused. Moreover, it was found that the shape of angular distortion was determined by the relative position of welding heat source and the position of the neutral axis in the flange, regardless of the position of the neutral axis in the fillet welded object.

Here, a series of three-dimensional thermal elastic-plastic analyses[1)] is performed by changing the welding conditions. Based on the results of the analyses, the characteristics of out-of-plane deformation and residual stress in fillet welding are elucidated. Moreover, the generality of the production mechanism for out-of-plane deformation is investigated based on the results of analyses performed by changing the welding conditions.

The deformation of the welding line direction (longitudinal bending deformation) and the deformation perpendicular to the welding line (angular distortion) are noted as out-of-plane deformations.

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2. Effect of the Welding Sequence on Out-of-Plane Deformation and Residual Stress

Figure 1 shows the fillet welding object, the coordinate system and sizes. The dotted line in the figure expresses the position of the neutral axis for the cross section of the model. Here, four types shown in the figure are provided.

The base material is mild steel. **Figure 2** shows the physical constants and mechanical properties of the mild steel. Welding speed v=6 (mm/s) and the welding heat input Q=1200 (J/mm) are fixed. ① and ② in the figure express the welding sequence.

The generality of production mechanism of out-of-plane deformation is investigated.

Figure 3 shows an example of the isothermal contours obtained by 3D non-steady heat conduction analysis.

2.1 Longitudinal bending deformation

Figure 4(a) shows longitudinal bending deformation at the top of the web (z=135(mm)).

The magnitude of deformation becomes larger in the order, Type Ⅰ, Type Ⅳ, Type Ⅱ, Type Ⅲ. As a result, the magnitude of deformation produced in continuous welding performed from one side to the other side is the smallest. It is considered that this is because the welding heat input seems to be smaller compared to the welding heat input of other types, as the heat given by the former welding has already diffused when the shrinkage due to the following welding occurs.

The welding heat source of each type exists below the neutral axis. The shape of the longitudinal bending displacement is convex. The generality of the production mechanism is proved.

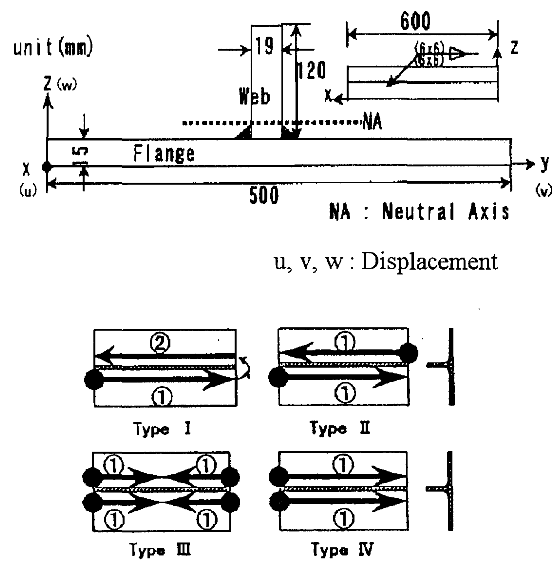
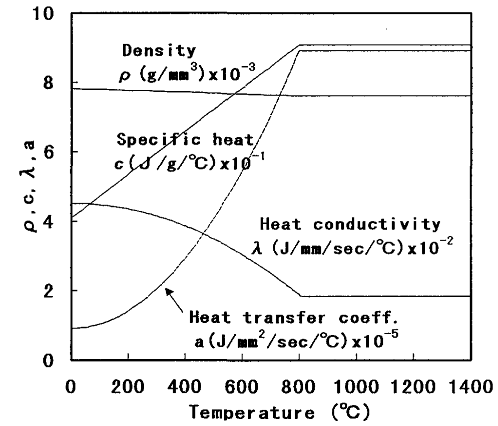
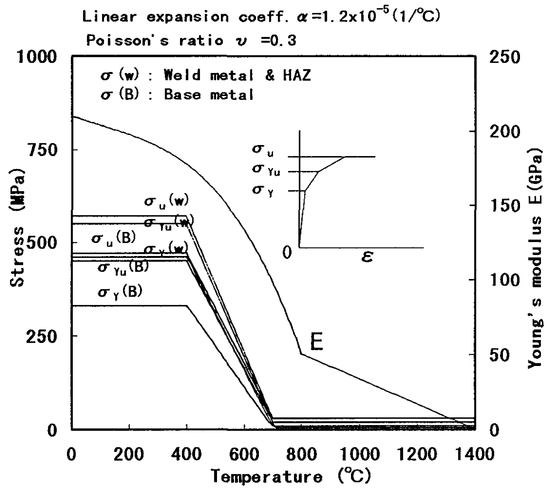


Fig.1 Model sizes and coordinate system.



(a) Physical constants.



(b) Mechanical properties.

Fig.2 Materials constants.

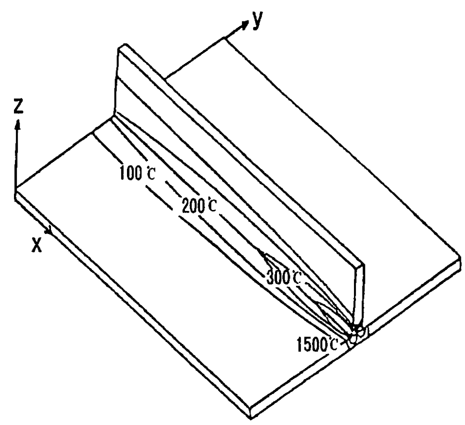
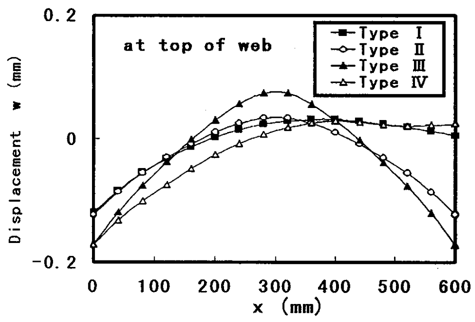
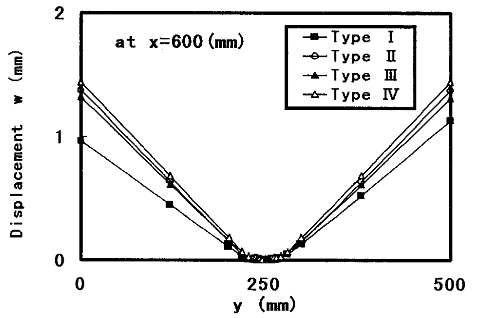


Fig.3 Isothermal contours.

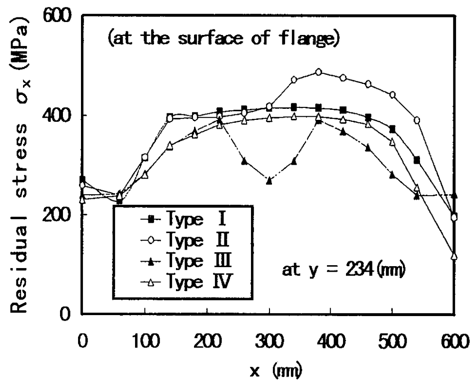


(a) Longitudinal bending displacement.

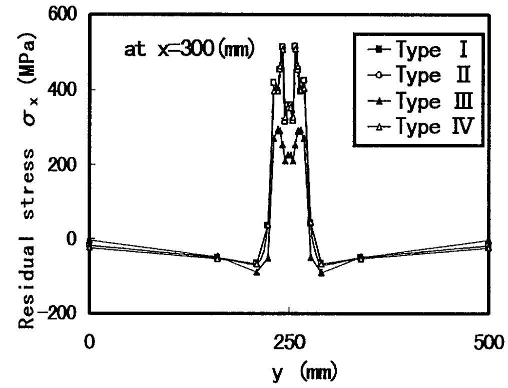


(b) Angular distortion.

Fig.4 Effect of welding sequence on out-of-plane deformation.



(a) Distribution along the welding line.



(b) Distribution perpendicular to the welding line.

Fig.5 Effect of welding sequence on residual stress.

2.2 Angular distortion

Figure 4(b) shows angular distortion at the end of the plate (x=600(mm)).

The magnitude of angular distortion produced by Type **I**, in which welding is continuously performed from one side to the other side, is the smallest. The reason was mentioned above. However, its magnitude differs in left and right sides.

As the welding heat source exists above the neutral axis of flange. The shapes of angular distortion are the same irrespective of the welding sequence. The generality of the production mechanism is proved.

2.3 Residual stress

Although the stress component σ_x in the direction of the weld line produced in fillet welding is large, other components are not so large[2]. Here, σ_x is examined.

Figure 5 shows the distribution along the welding line of σ_x generated at the toe of the flange (y=234(mm), z=15(mm)) and the distribution perpendicular to the welding line at the central position (x=300(mm), z=15(mm)).

Generated residual stress is largely influenced by the welding sequence. The absolute value of σ_x generated in Type III is the smallest. The heat is hard to diffuse in front of the heat source as the characteristic of thermal diffusion in the moving heat source. So, it is considered that the absolute value of σ_x generated in Type III, in which welding is finished at the central position, is the smallest. Type II indicates that residual stress is largely influenced by the former welding (Fig.5(a)).

3. Effect of the Welding Speed on Out-of-Plane Deformation and Residual Stress

The case where fillet welding is performed on both sides at the same time is examined (Type IV). The welding heat input Q=1200(J/mm) is fixed and the welding speed, v, is changed to 3, 6, 9, ∞ (mm/s). The welding speed of ∞ (mm/s) represents an instantaneous heat source.

The generality of the production mechanism of out-of-plane deformation is investigated.

3.1 Longitudinal bending deformation

Figure 6(a) shows longitudinal bending deformation.

In the case of the instantaneous heat source, longitudinal bending displacement is largely produced because the shrinkage occurs on the whole welding line at the same time. The magnitude of longitudinal bending displacement does not make so large difference in the actual welding when the welding heat source moves.

As the neutral axis exists above the welding heat source, convex longitudinal bending deformation is produced even if the moving speed of the welding heat source is changed. So, the generality of the production mechanism is proved.

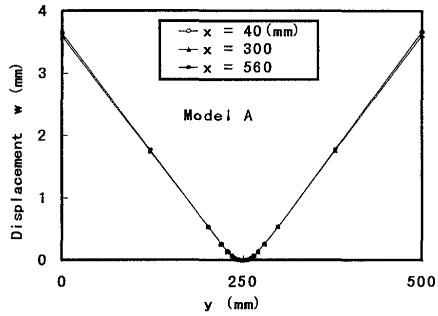
3.2 Angular distortion

Figure 6(b) shows angular distortion.

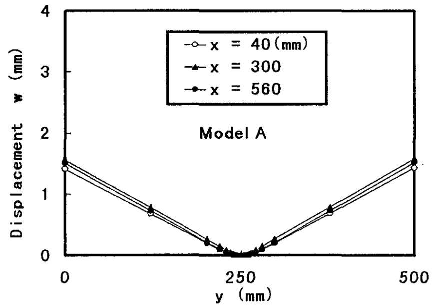
The magnitude of angular distortion is the largest in the case of the instantaneous heat source (the welding speed is infinite). However, even if the welding speed becomes fast, the magnitude does not converge to the value obtained by the instantaneous heat source in the case of a moving heat source, but tends to converge to a limit value within the finite speed. This result indicates that the welding heat source should not perform as an instantaneous heat source but as a moving heat source when the problem of welding deformation is investigated.

The shape of angular distortion is the same, even if the welding speed changes. The generality of the production mechanism is proved.

On the other hand, although the magnitude of angular distortion is same at the central position and the starting and finishing edges of welding in the case of the instantaneous heat source (**Fig. 7(a)**), it is different at the central position and the starting and finishing edges of welding in the case of the moving heat source (**Fig. 7(b)**).

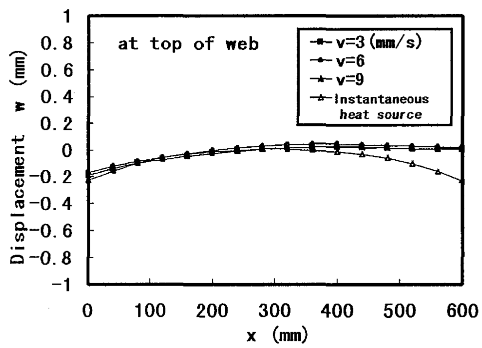


(a) Instantaneous heat source.

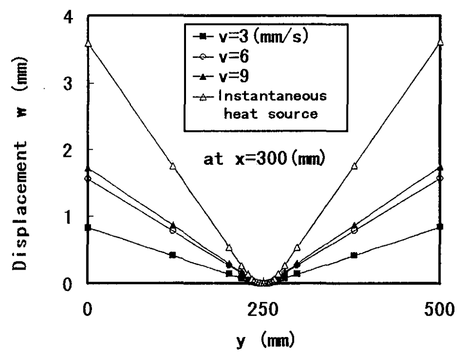


(b) Moving heat source.

Fig.7 Effect of welding speed on angular distortion.



(a) Longitudinal bending displacement.



(b) Angular distortion.

Fig.6 Effect of welding speed on out-of-plane deformation.

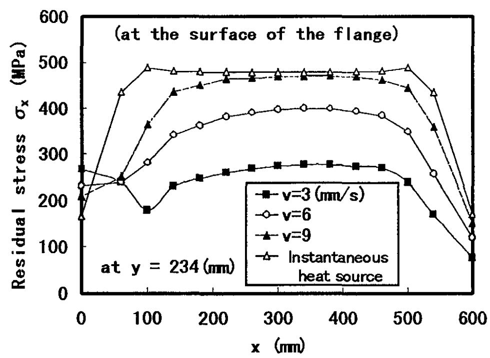


Fig.8 Effect of welding speed on residual stress.

3.3 Residual stress

Figure 8 shows the distribution of σ_x along the weld line generated at the toe on the flange surface.

σ_x is largely influenced by the moving speed of the heat source. The faster the welding speed becomes, the larger σ_x generates. When the welding speed becomes faster, residual stress at the central position coincides well with the result of the instantaneous heat source in contrast to the welding deformation problem. The distribution shape of σ_x perpendicular to the weld line is the same as the above mentioned distribution of Type IV.

4. Effect of the Welding Heat Input on Out-of-Plane Deformation and Residual Stress

The case that a fillet weld is performed on both sides at the same time is examined (Fig. 1, Type IV). The welding speed v=6 (mm/s) is fixed and the welding heat input Q is changed to 1100, 1200, 1460, 1720 (J/mm).

The generality of the production mechanism of out-of-plane deformation is investigated.

4.1 Longitudinal bending deformation

Figure 9(a) shows longitudinal bending deformation. If the welding heat input becomes large, longitudinal bending deformation becomes large.

Convex deformation is produced even if the welding heat input is changed, because there is no change at the relative position of the welding heat input and the neutral axis. So, the generality of the production mechanism is proved.

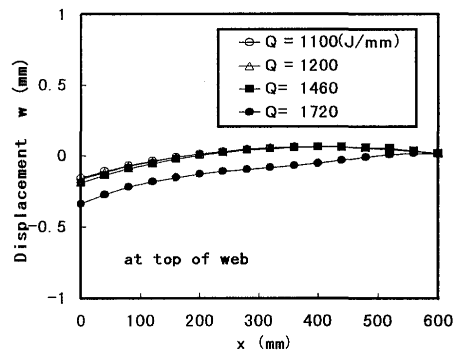
4.2 Angular distortion

Figure 9(b) shows angular distortion.

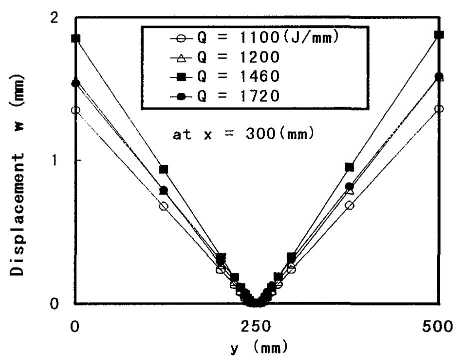
It has been usually mentioned that the larger the welding heat input becomes, the larger the angular distortion becomes. However, it was found that if the welding heat input became extremely large, angular distortion conversely became small. Assuming the flange thickness to be fixed and changing the welding heat input, a series of the analyses was performed so as to confirm the truth.

Figure 10 shows the results of the analyses.

Angular distortion tends to become small when the welding heat input for each flange thickness exceeds a certain value. This is because the temperature gradient in the thickness direction becomes small when the welding heat input for the flange thickness becomes large. By these results, the validity of the phenomenon is supported.



(a) Longitudinal bending displacement.



(b) Angular distortion.

Fig.9 Effect of welding heat input on out-of-plane deformation.

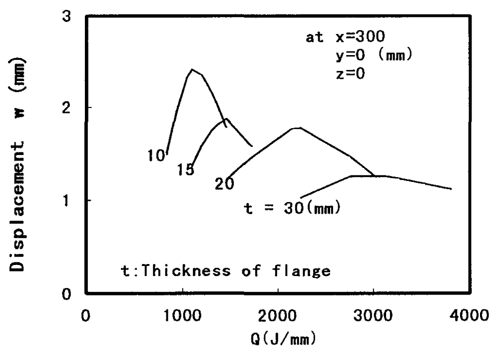


Fig.10 Effect of welding heat input on angular distortion.

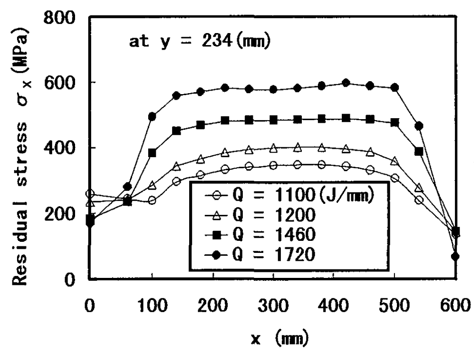


Fig.11 Effect of welding heat input on residual stress.

The shape of the deformation is the same, even if the welding heat input changes. The generality of the production mechanism is proved.

4.3 Residual stress

Figure 11 shows the distribution of σ_x along the weld line generated at the toe on the flange surface. When the welding heat input becomes larger, residual stress tends to be large. The distribution shape of σ_x perpendicular to the weld line is the same as the above mentioned distribution of Type Ⅳ.

5. Conclusion

To elucidate the characteristics of out-of-plane deformation and residual stress generated by fillet welding, a series of FEM analyses was performed by changing the welding conditions. The generality of the production mechanisms for out-of-plane deformation was investigated.

The results can be summarised as follows:

(1) Longitudinal bending deformation and angular distortion were largely influenced by the welding sequence. When welding was performed continuously from one side to the other side, the magnitude of out-of-plane deformation was the smallest. However, the magnitude of angular distortion was different for left and right sides.

Generated residual stress σ_x was largely influenced by the welding sequence.

(2) If the welding speed was within the range of the actual operation, longitudinal bending deformation was not influenced by changing the welding speed. Angular distortion was largely influenced. When the welding speed became fast, angular distortion tended to be large and to converge to a certain limit. However, attention should be paid to the fact that angular distortion was found to be large when it was estimated ignoring effect of the moving heat source.

The faster the welding speed became, the larger became the generated residual stress σ_x.

(3) Longitudinal bending deformation is not so largely influenced by changing the welding heat input. Angular distortion was largely influenced by the welding heat input and tended to be large until the relative welding heat input for the flange thickness reached a certain value. Then, when the welding heat input exceeded this certain value, angular distortion conversely became small.

Generated residual stress, σ_x, became large when the welding heat input became large.

(4) The generality of the production mechanisms for out-of-plane deformation was proved from the results of analyses performed by changing the welding conditions in fillet welding.

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2) Y.C. Kim et al. : Effects of Initial Imperfection on Out-of-Plane Deformation and Residual Stress Produced by Welding, Trans. of JWRI, 26-2(1997), pp.75-80.