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Prevention of Lamellar Tearing in Multipass Welded Corner Joint*

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Abstract

Lamellar tearing of opening type occasionally occurs in multipass welded corner joints. Effects of gas cutting for the edge surface of the vertical plate and shapes of groove on the occurrence of the lamellar tearing are investigated experimentally and theoretically. The main results obtained in this study are as follows.

(1) *In the cases where the edge surface of the vertical plate is prepared by gas cutting or machine, the transverse welding residual stress on the edge surface of the vertical plate reaches approximately the yield point at a position 10 mm away from the toe and the lamellar tearing occurs, when the intensity of bending restraint increases. No difference between these cases is observed in the critical intensity of bending restraint for lamellar tearing.*

(2) *In order to reduce transverse welding residual stresses and to prevent the occurrence of the lamellar tearing, it is effective to use such a groove that the edge of the vertical (web) plate is projected out of the upper surface of the flange plate or that the vertical plate is cut obliquely.*

1. Introduction

In corner joints used in bridges and industrial machinery, lamellar tearing of opening type occasionally occurs at a position apart from the heat-affected zone. In relation to this, the effect of the intensity of bending restraint[1),2)] on the occurrence of the lamellar tearing and the dynamical conditions for the occurrence of the lamellar tearing were investigated.[3),4)] As a result, it was revealed that lamellar tearing of opening type was caused principally by a large tensile welding residual stress on the edge surface of the vertical plate where the intensity of bending restraint was large.

In this paper, the effectiveness of detail design of multipass welded corner joints for preventing the occurrence of lamellar tearing of opening type is investigated. The occurrence of the lamellar tearing in specimens is examined with the aid of Corner Joint Weld Cracking Test (CJC-test)[3)]. In this test, a specimen with the edge surface of the vertical plate prepared by gas cutting or machine and several types of grooves are used. Welding residual stresses are calculated theoretically and measured with these specimens and grooves. Effects of gas cutting for the edge surface of the vertical plate and shapes of grooves on the occurrence of the lamellar tearing are investigated experimentally and theoretically.

2. Corner Joint Weld Cracking Test (CJC-test)

2.1 *Materials and Experimental Procedure*

The occurrence of the lamellar tearing in specimens is examined by use of Corner Joint Weld Cracking Test (CJC-test) apparatus[3)] as shown in Fig. 1. As

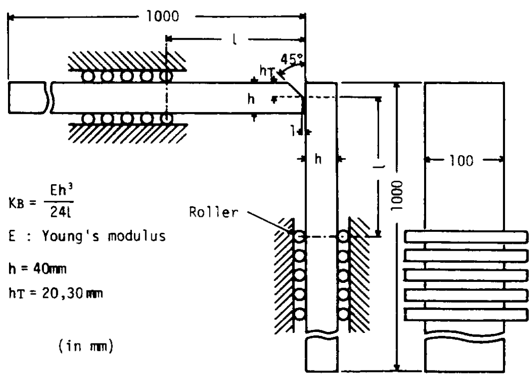

Fig. 1 Apparatus for Corner Joint Weld Cracking Test (CJC-test)

seen in this figure, the specimens are held down by the rollers and the angular distortion due to welding is not allowed at the inner ends of the rollers. Therefore, the intensity of bending restraint (K_B) can be chosen by adjusting the restraint length (l) but the intensity of tensile restraint is kept nought.

The steel plate used in this experiment is of 50 kg/mm^2 class high tensile strength steel, 40 mm thick. The chemical compositions and mechanical properties of the steel plate are shown in Table 1. Five types of grooves shown in Fig. 2 are used. In order to examine the effect of gas cutting for the edge surface of the vertical plate on the occurrence of the lamellar tearing, the CJC-test is carried out on a specimen with the edge surface of the vertical plate prepared by gas cutting (Type G) or machine (Type M), and the experimental results on two types of grooves are compared with each other. Furthermore, the remaining three types of grooves (Types P, W and C) are tested to examine the effectiveness for preventing the occurrence of the lamellar tearing. In the case of Type P, the projecting length (Δ_0) of

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Table 1 Chemical compositions and mechanical properties

Material	Thick. (mm)	Chemical composition (wt %)											Y.P.	T.S.
		C	Si	Mn	P	S	Cu	Ni	Cr	Mo	V	Ceq	kg/mm^2	kg/mm^2
SM50B	40	0.12	0.45	1.46	0.021	0.018	0.015	0.026	0.018	0.001	0.061	0.39	40	53
Weld M.	—	0.075	0.55	0.96	0.011	0.007	0.014	0.020	0.019	0.001	0.008	0.26	48	56

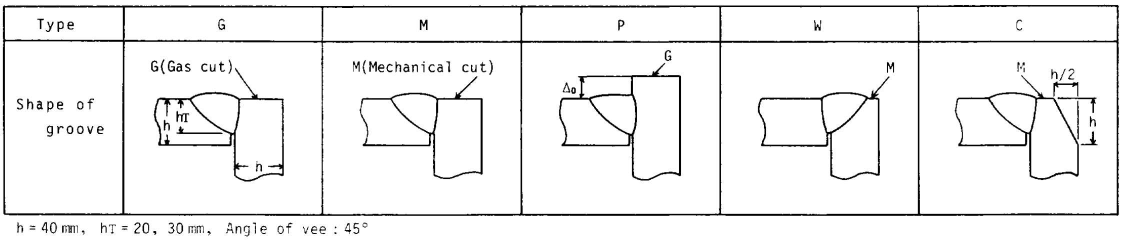


Fig. 2 Shapes of grooves used in CJC-test

Table 2 Welding conditions

Welding process	Welding rod	Preheat-ing temp.	Interpass temp.	Welding current	Welding voltage	Welding speed	Heat input
Covered arc	5 mmΦ	50 °C	50 °C	240 A	26 V	17 cm/min	22 kJ/cm

the vertical plate is varied in several ways.

Test welding is carried out by covered arc welding with welding rods of hydrogen level of 10 cc/100 g (the measured value by the method of JIS is 9.6 cc/100 g). The welding conditions are shown in Table 2.

After the specimens are kept under the restraint condition over eighty-four hours after welding, the occurrence of the lamellar tearing is examined at five to seven cross sections of each specimen.

2.2 *Experimental Results*

Lamellar tearing of opening type as shown in Photo. 1 was observed at a position about 10 mm away from the toe in the case of Type M as well as Type G. The result of the CJC-test is shown in Fig. 3. As seen in this figure, the critical intensity of bending restraint for lamellar tearing (K^l_{Bcr})[3] in the case of Type M is 400×10^3 kg·mm/mm·rad which is the same value as K^l_{Bcr} in the case of Type G.

Photographs 2 and 3 are microphotographs of the lamellar tearing which occurred in Types G and M respectively. In these cases, two kinds of lamellar tearings are observed; one which opens widely at the surface (Photos.2(a) and 3(a)) and the other which seems to open a little below the surface and then propagate to the surface (Photos.2(b), 2(c) and 3(b)). The fracture morphology of the lamellar tearing was examined with the aid of a scanning electron microscope and an energy dispersive X-ray analyzer. As a result, many elongated manganese sulphide inclusions were observed on terrace fracture, and any noticeable difference in the fracture morphology was not seen in Types G and M.

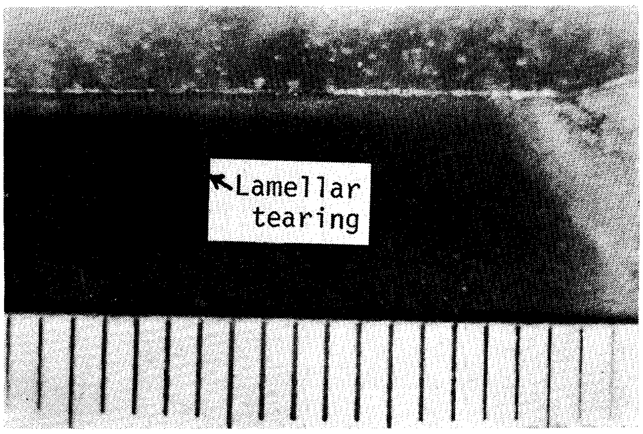


Photo. 1 Macrophotograph of lamellar tearing (Type M, h_T=30 mm)

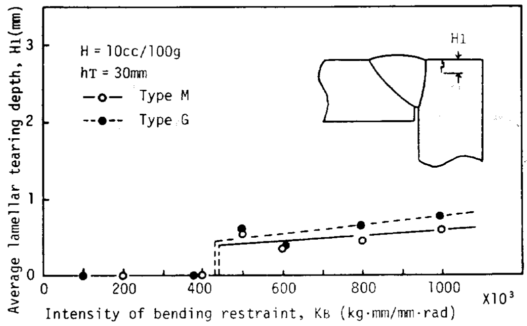
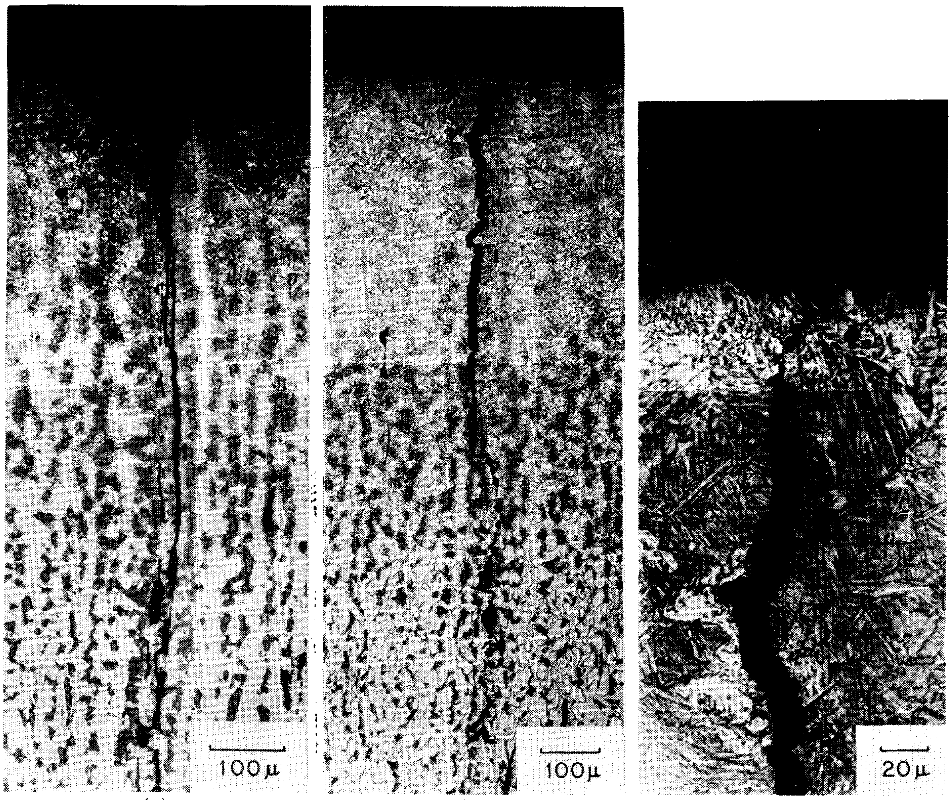


Fig. 3 Relation between lamellar tearing and intensity of bending restraint

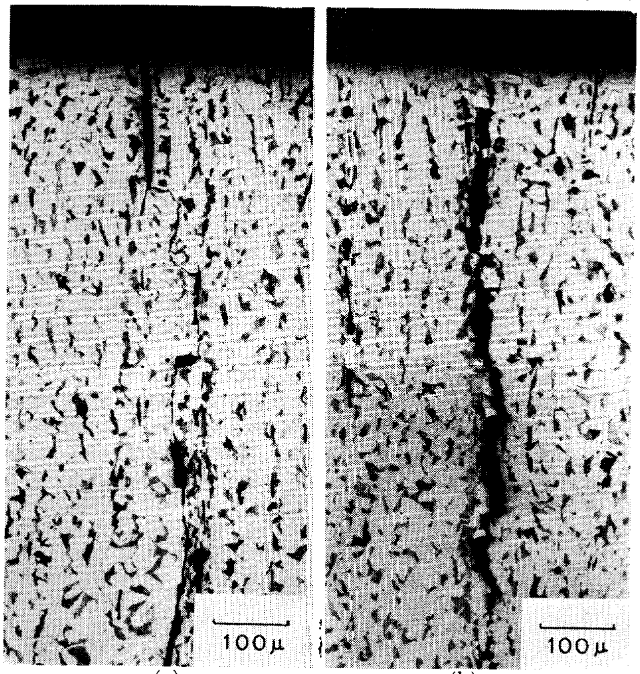
As mentioned above, the critical intensities of bending restraint for lamellar tearing and fracture morphologies are almost the same in the cases of Types G and M. It is appropriate to understand that whether the lamellar tearing occurs from the surface or a little below the surface and then propagates to the surface is mainly dependent upon the distribution of manganese sulphide inclusions.

Figure 4 shows the result of the CJC-test in the case of Type P. As seen in this figure, lamellar tearing



(a) (b) (c)

Photo. 2 Microphotographs of lamellar tearing (Type G, $h_T=30$ mm, (c); magnified photograph of photo. (b))



(a) (b)

Photo. 3 Microphotographs of lamellar tearing (Type M, $h_T=30$ mm)

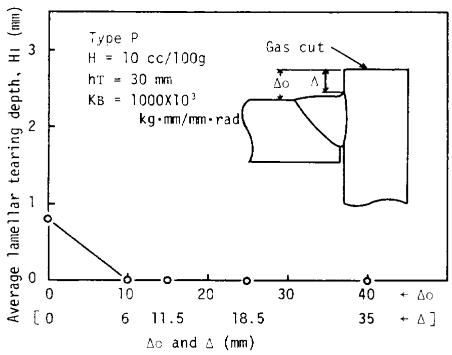
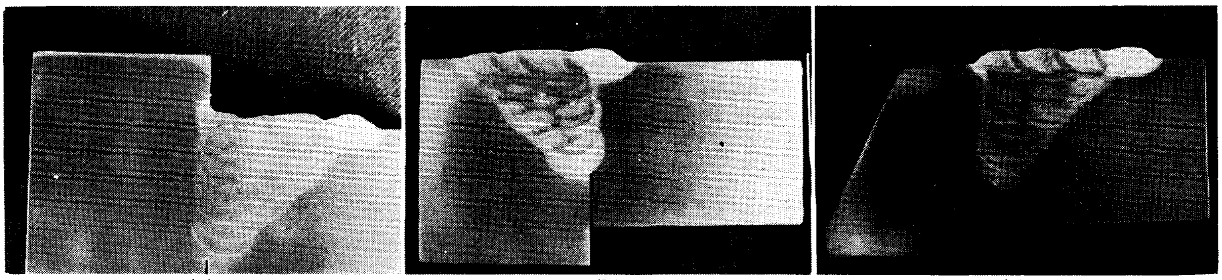


Fig. 4 Relation between lamellar tearing and Δ_0 (Δ)

does not occur when the edge of the vertical plate is projected more than 10 mm ($\Delta_0 \geqq 10$ mm).

In the cases of Types W and C, lamellar tearing does not occur even where $K_B=1000\times10^3$ kg·mm/mm·rad. Examples of macrophotographs of these weldments are shown in Photo. 4.



(a) (b) (c)

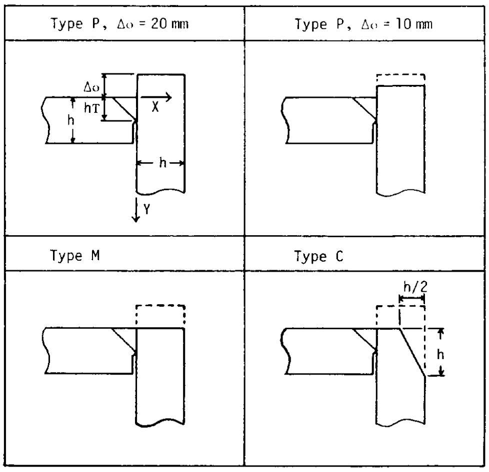
Photo. 4 Macrophotographs of weldments ($h_T=30$ mm) (a) Type P, (b) Type W, (c) Type C

3. Welding Residual Stress

3.1 *Methods of Analysis and Measurement*

The transverse welding residual stress (σ_x) distribution is calculated by use of the finite element method (F.E.M.) in a state of plane stress through the thermal elastic-plastic (Th-El-Pl) analysis which was described in the previous paper[4]. The σ_x-distribution is obtained for Types M and P (Δ_0=20 mm) where h_T=20 mm and K_B=1000×10^3 kg·mm/mm·rad. Furthermore, the σ_x-distribution is calculated by the elastic-plastic (El-Pl) analysis of the F.E.M. when the shape of the groove is changed by cutting from Type P (Δ_0=20 mm) to Types P (Δ_0=10 mm), M and C as shown in Fig. 5. In this process of calculation, the σ_x-distribution for Type P (Δ_0=20 mm) calculated by the Th-El-Pl analysis mentioned above is used as the initial condition. The mesh division of Type P (Δ_0=20 mm) for the El-Pl analysis is shown in Fig. 6.

The welding residual stress is measured by the sectioning method with strain gages (gage length=2 mm, gage width=2 mm).



h = 40 mm, hT = 20 mm, Angle of vee : 45°
KB = 1000X10³ kg·mm/mm·rad (l = 56 mm)

Fig. 5 Shapes of grooves for elastic-palstic analysis

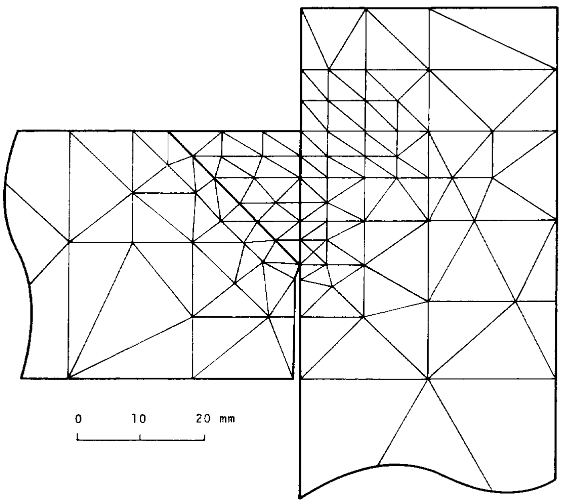


Fig. 6 Mesh division for elastic-plastic analysis

3.2 *Results of Analysis and Measurement*

Figure 7 shows the result of the measurement of the transverse welding residual stress (σ_x) distribution on the edge surface of the vertical plate in the cases of Types G and M where h_T=30 mm and K_B=1000×10^3 kg·mm/mm·rad. In both cases the stress σ_x reaches the maximum value at a position apart from the toe. The stress σ_x for Type G is larger than that for Type M by about 10 kg/mm^2. This difference[4] can be attributed to the superposition of the residual stress through thickness due to gas cutting, which is about 10 kg/mm^2.

Figure 8 shows the relation between K_B and σ_x on the edge surface of the vertical plate at a position 10 mm away from the toe and the relation between K_B and the angular distortion due to welding. As seen in this figure, the stress σ_x in each case increases with an increase of K_B, and it reaches a constant value, which seems considerably large, when K_B becomes more than 200×10^3 kg·mm/mm·rad. This constant value is from 42 to 48 kg/mm^2 in the case of Type G and from 34 to 38 kg/mm^2 in the case of Type M. These values correspond approximately to the yield point (which is to be shown in Fig. 12) observed in the tension test through thickness for the heat-affected zone due to gas cutting (ZG) and to the yield point through thickness (Z) respectively. The change of the angular distortion due to welding against K_B shows a contrary tendency to the σ_x·K_B relation. These two relations indicate an apparent corelation between them.

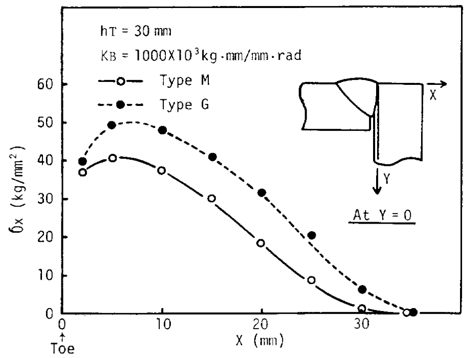


Fig. 7 Transverse welding residual stress distributions measured experimentally

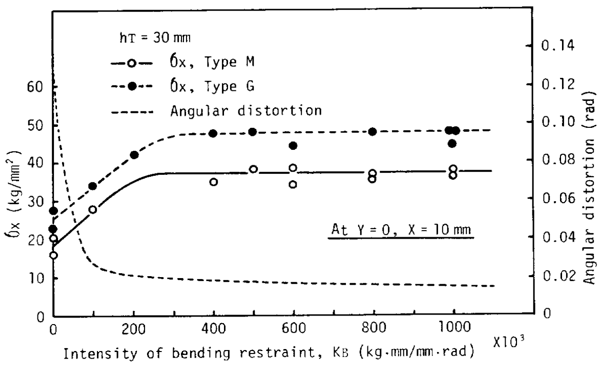


Fig. 8 Effects of intensity of bending restraint on transverse welding residual stress and angular distortion

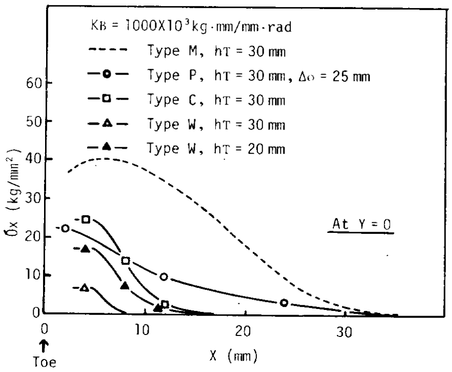


Fig. 9 Transverse welding residual stress distributions measured experimentally

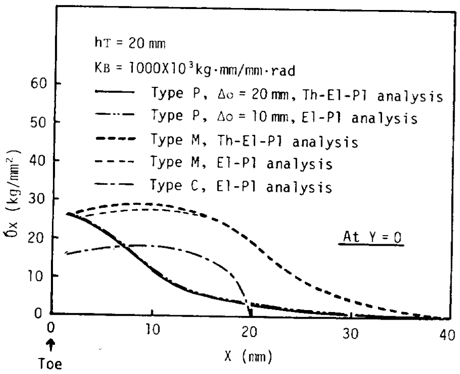


Fig. 10 Transverse welding residual stress distributions analyzed theoretically

Figure 9 shows the result of the measurement of the σ_x-distribution in the cases of Types P (Δ_0=25 mm), W and C. As seen in this figure, the stress σ_x in every case is less than that in the case of Type M. As the result of the measurement of the σ_x-distribution in the case of Type P (Δ_0=10, 15 and 40 mm), the σ_x-distribution was seen almost the same as that in the case of Type P (Δ_0=25 mm) as shown in Fig. 9.

Figure 10 shows the result of the El-Pl analysis of the σ_x-distribution in the cases of Types P (Δ_0=10 mm), M and C. It also shows the result of the Th-El-Pl analysis of the σ_x-distribution in the cases of Types P (Δ_0=20 mm) and M. As seen in the figure, the results of the El-Pl analysis and the Th-El-Pl analysis of the σ_x-distribution agree well with each other. Therefore, it is considered that the change of σ_x-distribution due to the change of the shape of the groove by cutting can be deduced by the El-Pl analysis using the σ_x-distribution calculated by the Th-El-Pl analysis as the initial condition. According to the result of the analysis as shown in Fig. 10 as well as that of the measurement, the stress σ_x for Types P and C is less than that for Type M and the σ_x-distributions in the cases of Δ_0=20 mm and Δ_0=10 mm in Type P are almost the same.

4. Small Tension Test

Figure 11 shows two kinds of test specimens for tension test furnished in this research. As seen in this figure, one specimen is of a circular cross section

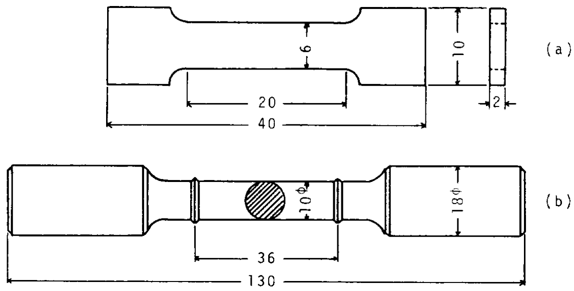


Fig. 11 Test specimens for tension test

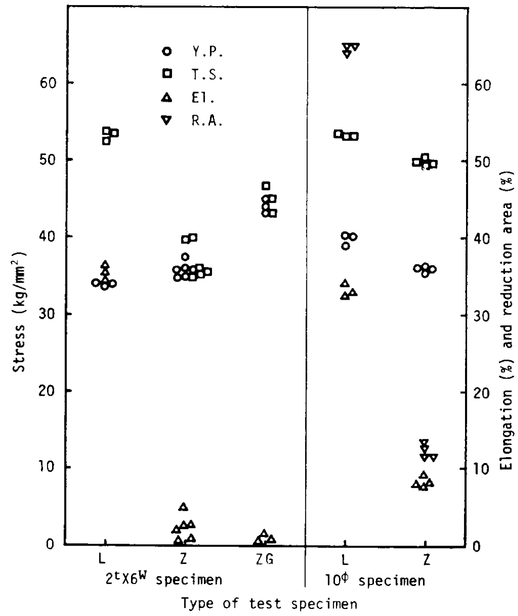


Fig. 12 Results of tension tests

and the other is small and flat. The test specimens are taken from the plate in the rolling direction (the specimen is designated as L) and through thickness (Z). Furthermore, as for the tension test of small flat, the specimen is taken from the heat-affected zone due to gas cutting through thickness (ZG).

As the result of the tension test, the specimen L showed a rupture of cup and cone. In the cases of specimens Z and ZG, it was seen that small tears occurred above the yield point. The results of the tension tests are summarized in Fig. 12. As seen in this figure, elongations of the specimens Z and ZG are considerably small compared with those of the specimen L. Elongation of the circular specimen Z is about 8 % and the result is scattered in a narrow range. On the other hand, elongations of small flat specimens Z and ZG are very small and the results are scattered widely. It is also seen that the yield point of the specimen Z is about 36 kg/mm² but that of the specimen ZG is larger, being about 44 kg/mm².

5. Discussion

In the cases of Types G and M, the transverse welding residual stress (σ_x) on the edge surface of the vertical plate reaches the maximum value at a position apart from the toe. The shrinkage due to welding is composed both of the X-direction and the Y-direction compoments. As it departs from the welded zone, the transverse stress induced by the former component decreases. The latter component induces a local bending deformation on the edge surface of the vertical plate, a compressive transverse stress near the welded zone and a tensile transverse stress at a position apart from the welded zone. It is considered that the resulting transverse welding residual stress distribution is a superposition of these two distributions.

In the cases of Types G and M, the stress σ_x on the edge surface of the vertical plate reaches approximately the yield point at a position 10 mm away from the toe and the lamellar tearing occurs near the edge surface of the vertical plate, when the intensity of bending restraint (K_B) increases. The result of the CJC-test shows that the lamellar tearing frequently occurs at a position 10mm away from the toe.[4] This result can be understood from the following facts: The stress σ_x reaches approximately the yield point at the position and there are more elongated manganese sulphide inclusions at the inner part of the plate thickness than at the surface.

A portion near the edge surface is considered approximately to be in a state of plane stress. Moreover, according to the result of the measurement of the longitudinal welding residual stress (σ_z) in the case of Type M, the observed stress σ_z is in the range -1 to $+7$ kg/mm^2 on the edge surface of the vertical plate at a position 10 mm away from the toe so that the stress σ_z is not considered to be influential on the occurrence of the lamellar tearing. Therefore, a state of stress near the edge surface of the vertical plate at a position about 10 mm away from the toe can be considered similar to that of the flat tension test specimen.

In the tension test of small flat specimens, scattering of the observed elongations through thickness is wider than that in the rolling direction. Elongation through thickness seems to be affected by the distribution of manganese sulphide inclusions.

In the case where the edge of the vertical plate is projected more than 10 mm ($\Delta_0 \geqq 10$ mm) in Type P, compared with the case of Type M, the local flexural rigidity near the groove becomes larger and the local bending stress induced by the thermal shrinkage in Y-direction decreases at a position apart from the welded zone. Therefore, the stress σ_x decreases at a position apart from the welded zone and the lamellar tearing is less probable to occur. Additionally, the σ_x-distribution does not change remarkably with Δ_0 where $\Delta_0 \geqq 10$ mm.

As in the cases of Type W and C where the vertical plate is cut obliquely, the local flexural rigidity near the groove becomes smaller and the stress σ_x on the edge surface of the vertical plate decreases. Therefore, the lamellar tearing is less probable to occur.

6. Conclusions

In this paper, effects of gas cutting for the edge surface of the vertical plate and shapes of grooves in multipass welded corner joints are investigated on the occurrence of lamellar tearing of opening type experimentally and theoretically. The main results obtained in this study are as follows:

(1) In the case where the edge surface of the vertical plate is prepared by gas cutting (Type G) or machine (Type M), the transverse welding residual stress (σ_x) on the edge surface of the vertical plate reaches approximately the yield point at a position 10 mm away from the toe and the lamellar tearing occurs, when the intensity of bending restraint (K_B) increases. No difference between these cases is observed in the critical intensity of bending restraint for lamellar tearing (K^l_{Bcr}) (Figs. 3, 7 and 8).

(2) In the case where the edge of the vertical (web) plate is projected out of the upper surface of the flange plate (Type P), the local flexural rigidity near the groove increases. Consequently, the local bending stress induced by the thermal shrinkage in Y-direction decreases at a position apart from the welded zone, and the stress σ_x decreases. Therefore, in order to prevent the occurrence of the lamellar tearing, it is effective to use a groove of Type P without changing the intensity of bending restraint (Figs. 4, 9 and 10).

(3) In the cases where the vertical plate is cut obliquely (Types W and C), the local flexural rigidity near the groove decreases. This results in a decrease of the stress σ_x on the edge surface of the vertical plate. Therefore, in order to prevent the occurrence of the lamellar tearing, it is also effective to use the grooves of Types W and C (Figs. 9 and 10).

Acknowledgement

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References

1) K. Satoh, I. Nishimura, H. Iiyama, N. Chiba, S. Hasebe, K. Bessho, S. Matsui and K. Horikawa; Study on Weld Cracking Behavior in Large Structures, Jl. of Society of Steel Construction of Japan, 11–118 (1975), 29–35 (in Japanese)

2) K. Satoh, S. Matsui, I. Nishimura, H. Iiyama and N. Chiba; Effect of Intensity of Bending Restraint on Weld Cracking in Multipass Weld, Trans. JWS, 8–1 (1977), 42–49, IIW Doc. IX-960-76, X-621-76, Jl. JWS, 45-11 (1976), 952–960 (in Japanese)

3) Y. Ueda, I. Nishimura, H. Iiyama and N. Chiba; Effects of Intensity of Bending Restraint on Lamellar Tearing and Root Cracking in Corner Joint, Trans. JWS, 8–2 (1977), 150–157, IIW Doc. IX-1018-77, Jl. JWS, 46–7 (1977), 408–415 (in Japanese)

4) Y. Ueda, K. Fukuda, I. Nishimura, H. Iiyama and N. Chiba; Dynamical Characteristics of Weld Cracking in Multipass Welded Corner Joint, Trans. JWS, 8–2 (1977), 138–142, IIW Doc. IX-1019-77, Jl. JWS (to be published)