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ABSTRACT

Fatigue strength of sound welded joints is affected not only by stress concentration due to structural discontinuity and local shape of weld toe but also by residual stresses. It is known that welding sequence makes the change of welding residual stress distribution. However, the assessing method of residual stress distribution with considering the effect of welding sequence for complicated welded structures has not been established yet.

For a partial double bottom model with a stool and a longitudinal girder, the method of superposition of welding residual stress distribution due to single pass weld line which can be assessed by inherent stress methodology is investigated by considering peak temperature due to current welding and the effect of welding sequence on elastic FEM model. Moreover, the line heating location and condition determined to change the tensile residual stress into compressive one as large as possible are used.

It is confirmed that residual stress distribution can be assessed by considering the heating sequence which include welding and gas heating. Fatigue strength was also discussed after assessing welded residual stress distribution.

INTRODUCTION

Fatigue cracks in steel ships often occur at the fillet weld toe of structural discontinuity parts where stress concentrations due to the joint geometry are relatively high and the fatigue strength of the weld is reduced in comparison to that of the base metal. This becomes more critical in ships which is built of high strength steels because the fatigue strength of steel in the as-welded condition does not increase in proportion to the yield or tensile strength. As a result, fatigue strength of welded details can be a limiting factor for the design of more efficient ship structures.

One possible reason why fatigue strength of welded structures does not increase in proportion to the yield strength may be the existence of welding residual stress which becomes usually larger as the yield strength increases. However, welding residual stress may be affected by welding sequence. Therefore it may be possible to enhance the fatigue strength of welded steel structures by selecting an adequate welding sequence. Then we selected a welded structural element which was modified for a double bottom structure with a stool in a tanker to study the effect of welding sequence on residual stress distribution and fatigue strength. With an intention of maximum compressive residual stress generated after welding, the line heating technique was also applied for the purpose of studying the effect of enhancement of fatigue strength from the view point of practical usage.

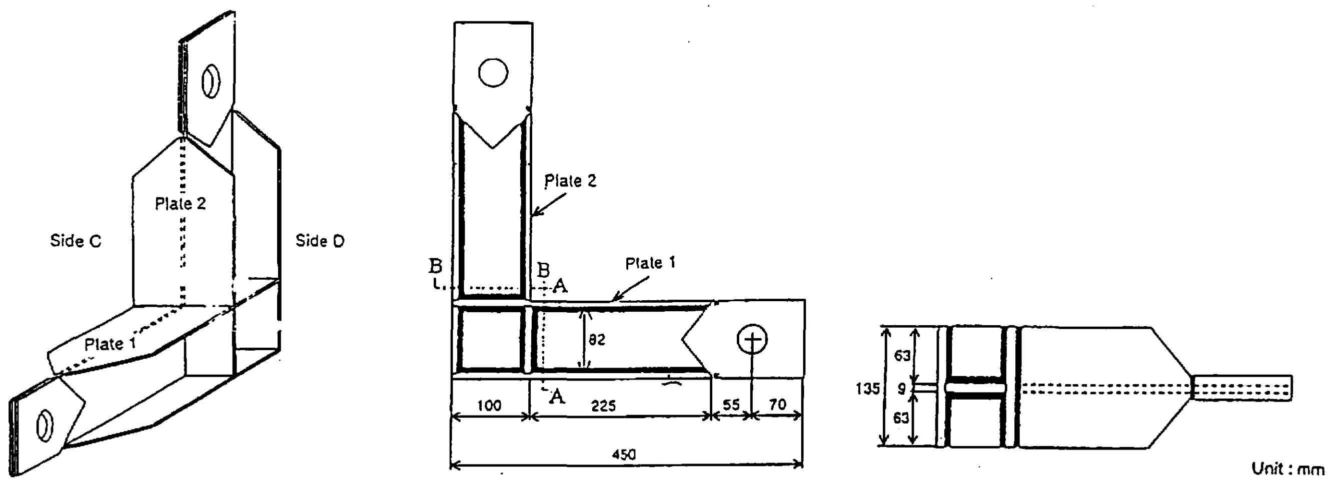

Fig. 1 Configuration of test specimen

Welding residual stress distribution for single pass welding can be assessed by using a finite element method with the aid of inherent stress methodology (Matsuoka, 1983). However, the method of considering the effect of welding sequence in the case of adopting the inherent stress methodology had not been established yet. This method is also investigated in this paper.

STRUCTURAL ELEMENTAL SPECIMEN

Figure 1 shows the specimen configuration used here which models the bottom structure of double hull tanker. In these specimens, plate 1 and 2 correspond to an inner bottom plate and a stool plate respectively and the web corresponds to a longitudinal girder.

Quite large amounts of fatigue cracking originated from the fillet weld toe, where the stool plate and the inner bottom plate overlap each other crosswise, at the girder location are reported and the configuration of specimens selected to study the fatigue crack sensitivity of welded structural elements.

Considering the residual stress on the surface of plate 1 and 2 near the overlapped section, two kinds of welding sequences in these specimens construction were adopted. These welding sequence were illustrated in Figs.2 (specimen A) and 3 (specimen B). The final weld line numbered 33 in Fig.3 corresponds to the fillet weld on the outside of the overlapped place between plate 1 and plate 2. On the contrary, the final weld is not the fillet weld on the outside of the overlapped place in Fig.2. As a result, the welding residual stress at the center of the outside overlapped place between plate 1 and 2 of Fig.3 was expected to be larger than that of Fig.2. Specimen A was made of SS400 steel and specimen B of KA32 steel, where SS400 steel has almost the same tensile strength as KA32 steel. CO_2 welding was adopted for these construction.

Several specimens were prepared both for specimens A and B. Residual stress distributions along AA and BB lines in addition to center line near the overlapped position as shown in Fig.1 were measured by stress relaxation method both for specimen A and B respectively in advance of fatigue testing. Two sets of specimens line heated to specimens A were also prepared. One is specimen C which was heated simultaneously along lines 9 [mm] apart from free edges, intending to generate maximum compressive residual stress on the plate surface at the center of the specimen (Toyosada and Yamaguchi,1994) and to enhance the fatigue strength after the construction of the elements. Another one is specimen D which was heated along center line to generate maximum tensile residual stress at the center surface of the specimen and to study the most deteriorated fatigue strength level for the specimen.

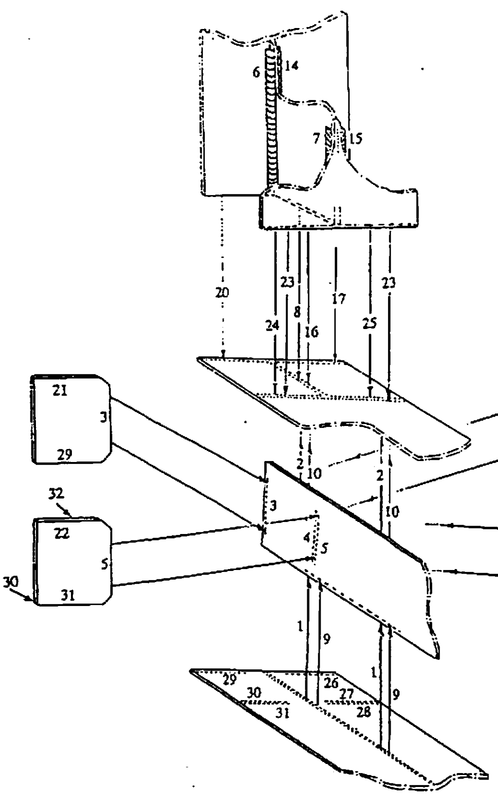

Fig. 2 Welding sequence of specimen A

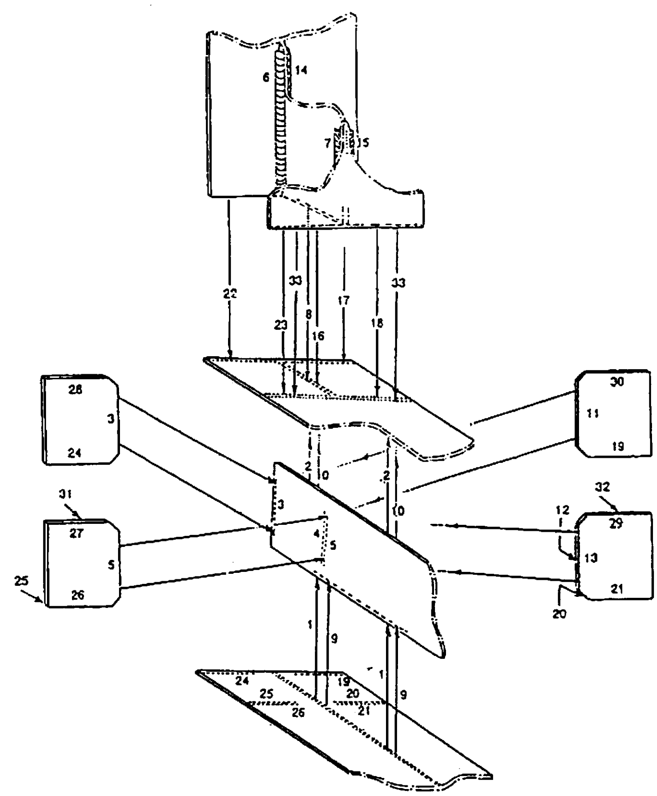

Fig. 3 Welding sequence of specimen B

BRIEF EXPLANATION OF ANALYTICAL CALCULATION FOR RESIDUAL STRESS DISTRIBUTION

Substituting inherent stress distribution which is calculated from welding heat input (Matsuoka, 1983) into the three dimensional elastic finite element cord, welding residual stress distribution for single pass welding could be obtained. However, the method for estimating the welding sequence effect on the residual stress for structural elements had not been established yet. Ma et al. (1996) suggested the estimation method of final residual stress distribution in the case of multi-layer welding. The following approximate equation could be derived from their result.

$$\sigma_{w1} = \sigma_{w0} + \kappa\sigma_{R0} \quad (1)$$

where

σ_{w1} : residual stress after completion of final welding

σ_{w0} : residual stress due to current welding for no residual stressed body

σ_{R0} : residual stress just before final welding

κ is a coefficient expressing the effects of initial stresses and is given by

$$\kappa = \begin{cases} 0 & \text{: for the region where maximum peak temperature due to current weld is beyond mechanical melting temperature} \\ r/a_0 & \text{: for the region where plastic deformation occur throughout the current welding} \\ 1 & \text{: for the region where plastic deformation does not occure throughout the current welding} \end{cases}$$

where

a_0 : distance from elastic-plastic boundary to mechanical melting boundary in current welding

r : distance from assessing point to mechanical melting boundary in current welding

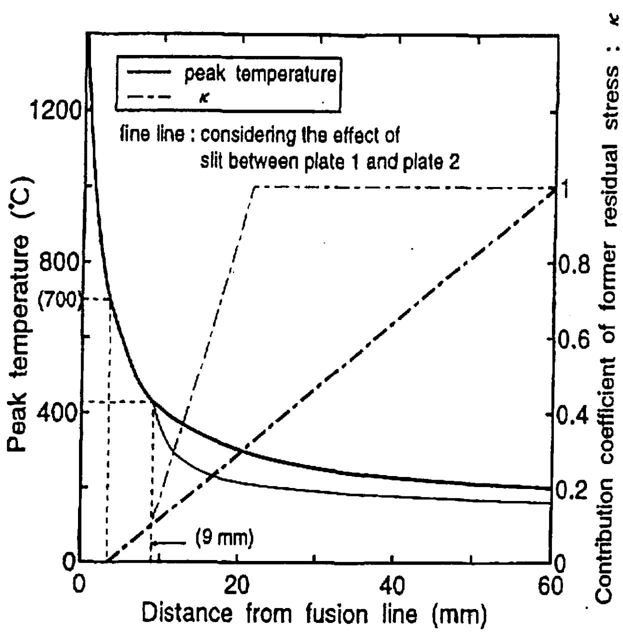

Fig. 4 Estimated peak temperature and contribution coefficient of former residual stress

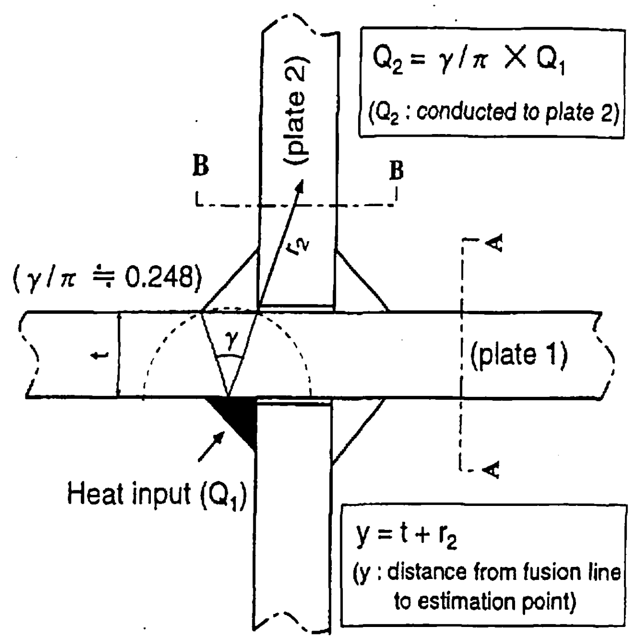

Fig. 5 Treatment of heat conducution for the effect of slit between plate 1 and 2

It is known that an elastic-plastic boundary throughout the welding corresponds to the location at which a maximum peak temperature reaches between 150 and 200 [°C]. The following equation which is modified Adams' equation was adopted for estimating the maximum peak temperature.

$$: \ 1/(\Theta_{max} - \Theta_0) = \lambda y + 1/(\Theta_{melt} - \Theta_0) \qquad (2)$$

where

Θ_{max}	:	maximum peak temperature
Θ_{melt}	:	melting temperature
Θ_0	:	interpass temperature
y	:	distance from a fusion line

The unknown coefficient λ in Eq.(2) could be determined by substituting the width of HAZ for y and postulating that the maximum peak temperature at HAZ boundary is 900 [°C]. In the calculation, following assumptions are made, i.e., Θ_{max} =1530 [°C] and Θ_0 =150 [°C], because welding was done continuously before a specimen cooled done completely by the former welding.

Figure 4 shows calculation results of maximum peak temperature in case of HAZ width of 1.9 [mm] which was an average value of HAZ for fillet welds for specimen A from macro structures (see the thick solid line). In this figure, the value of κ was also shown (see the thick alternate long and short dash line), postulating that the elastic-plastic boundary throughout the welding corresponds to the location at which a maximum peak temperature reached 200 [°C]. However, in case that the heat conducts through the fillet weld joint as shown in Fig.5, maximum peak temperature became smaller because most heat does not conduct through a slit. In this case, we postulated that the heat source is idealized as the point heat source and heat conducts radiately for simplicity. As a result, maximum peak temperature in plate 2 due to a fillet welding on back surface of plate 1 might be given by

$$1/(\Theta_{max} - \Theta_0) = \begin{cases} \lambda y + 1/(\Theta_m - \Theta_0) & (y \leqq t) \\ \lambda\{(y-t)(\pi/\gamma) + t\} + 1/(\Theta_m - \Theta_0) & (y \geqq t) \end{cases} \qquad (3)$$

The thin lines in Fig.4 show the result in case of the thickness of plate 1 of 9 [mm]. Although the welding was not done simultaneously, we assumed that welding which is symmetric with respect to the loading axis was done simultaneously for simplicity. An inherent stress for each welding

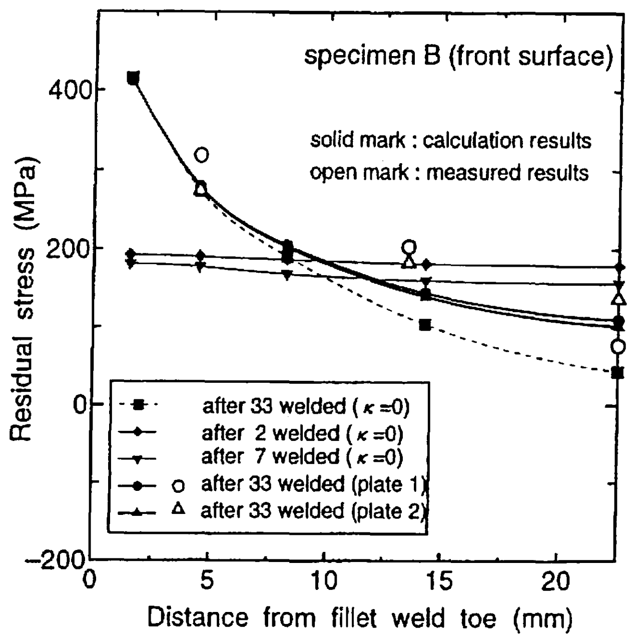

Fig. 6 Measured and calculated residual stress distributions on front surfaces of plate 1 and 2 along the center line for specimen B

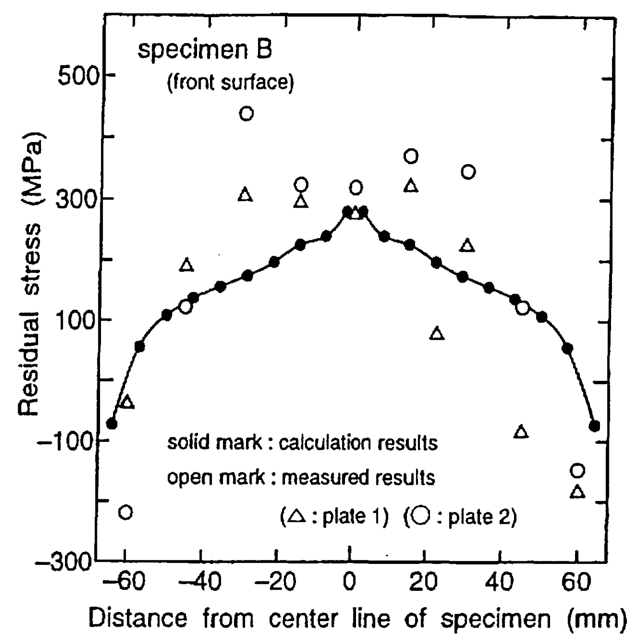

Fig. 7 Measured and calculated residual stress distributions on front surfaces of plate 1 (A-A section) and 2 (B-B section) for specimen B

was given to each element and residual stress for each welding is obtained. Superimposing each residual stress by using Eq.(1), welding residual stress distribution with considering welding sequence might be assessed.

RESIDUAL STRESS DISTRIBUTION

When maximum peak temperature due to the final welding is beyond a mechanical melting point, it is understood from Eq.(1) that former welding does not give any effect on residual stress. In other word, residual stress can be assessed only by a final welding for this position.

Figure 6 shows measured residual stresses along the center line on outer plate surface near the fillet weld between plate 1 and plate 2 for specimen B of which the welding sequence was shown in Fig.3. In the figure, residual stresses along the center line on outer surface of plate calculated separately and superposing by using Eq.(1) are shown. Calculated residual stresses due to final welding numbered 33 independently is a little smaller than measured ones, but assessed ones considering the effect of back side fillet welding between these plates and web numbered 2 or 7 in addition to final welding seems to be in good agreement with measured residual stresses.

Figure 7 shows measured and calculated residual stress along AA and BB cross sections, which is 4.5 [mm] away from fillet welded toes, on a outer plate surface for specimen B. At these positions, maximum peak temperature due to final welding numbered 33 in Fig.3 was beyond mechanical melting point of 700 [°C] and residual stress at these positions is considered to be generated only by final welding. Although measured residual stresses show large scattering, calculated ones are also in good agreement with measured ones.

Figure 8 shows residual stresses on outer surface of plate 2 at cross section of BB for specimen A. It is understood that assessed residual stress changes in a complicated way for each welding. However, it is seen that the assessed final residual stress distribution with considering the welding sequences is also in good agreement with the measured one. Figure 9 is for residual stress along center line of specimen A. It can be understood that residual stress changes easily depending on welding sequence. In other word, residual stress can be reduced largely by choosing an adequate welding sequence for welded structures. However, it is difficult to choose an adequate welding sequence in practice. But it

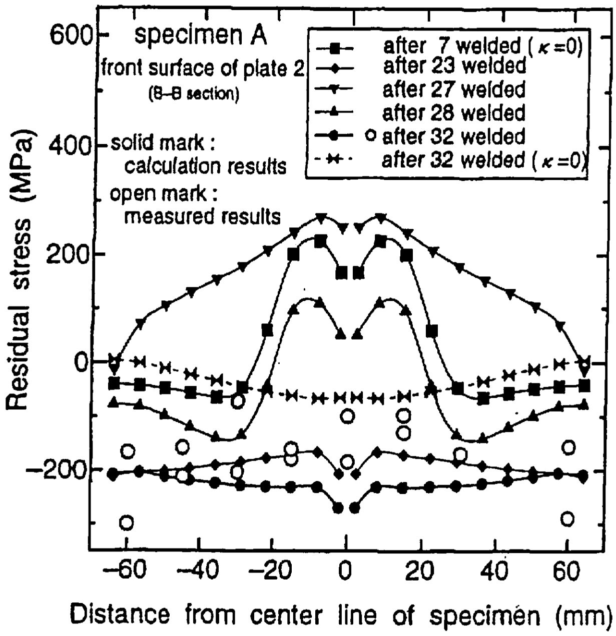

Fig. 8 Measured and calculated residual stress distributions on front surfaces of plate 2 (B-B section) for specimen A

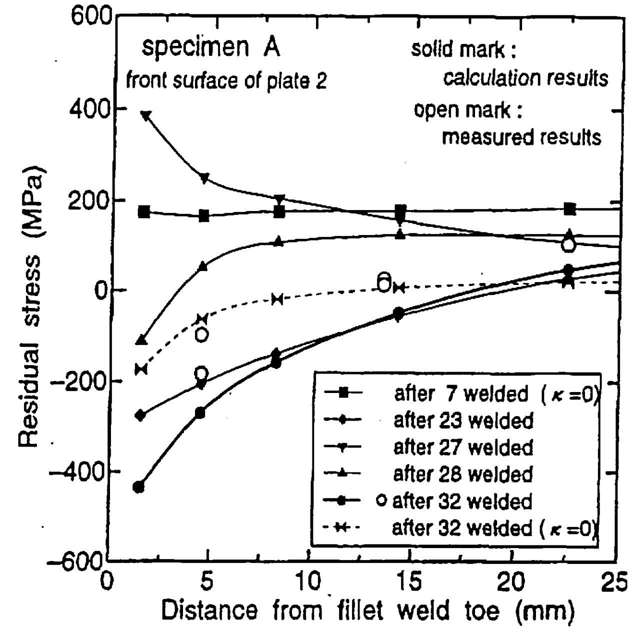

Fig. 9 Measured and calculated residual stress distributions on front surfaces of plate 2 along the center line for specimen A

is usually easy to specify the points with very large structural discontinuity where fatigue damage may occur due to high strain concentration. Large tensile residual stress usually exists at these parts and may cause structural fatigue strength to deteriorate. If residual stress at a high strain concentrated part could turn to be a large compressive side, it is expected to improve the fatigue strength of structures.

It is possible to generate compressive residual stress at a desired position by using line heating after welding. Theoretically speaking, maximum compressive residual stress level is about half of yield point. Determination method of the location of gas heating line for the purpose of generating maximum compressive residual stress at a specified part is already reported (Toyosada and Yamaguchi,1994). The highest strain concentration part of the specimen shown in Fig.1 is the fillet weld toe on plate outer surface at web position. According to this determination method, situation of gas heating lines is obtained. Figure 10 shows measured and calculated residual stresses for specimen C. It is seen that the calculated residual stress distribution is also in good agreement with the measured one and the expected maximum compressive stress with half of yield point appears at web position (center line). As a natural consequence of flame heating, it is seen that tensile residual stress with yield point level generates at heating positions. Figure 11 shows the calculation result of residual stress distribution after gas heating at center line. Although residual stress was not measured for specimen D, it is naturally understood from Fig.11 that the tensile residual stress which reached yield strength level was generated on the line heating position.

FATIGUE TEST RESULTS AND DISCUSSIONS

Constant amplitude fatigue tests with stress ratio of 0.05 were carried out for specimens A,B,C and D. Figure 12 shows the results where the vertical axis shows a gross surface stress at fillet weld toe position by elastic beam theory and the definition of failure on the horizontal axis is the number of cycles when loading control of servo pulsar could not keep because of very large displacement above 10 [mm]. The solid marks show these specimens on which fatigue crack initiated from fillet weld toe at center (at web position), where maximum strain concentration for structural discontinuity occurred. Specimens except specimen C had a crack initiated from fillet weld toe at web position.

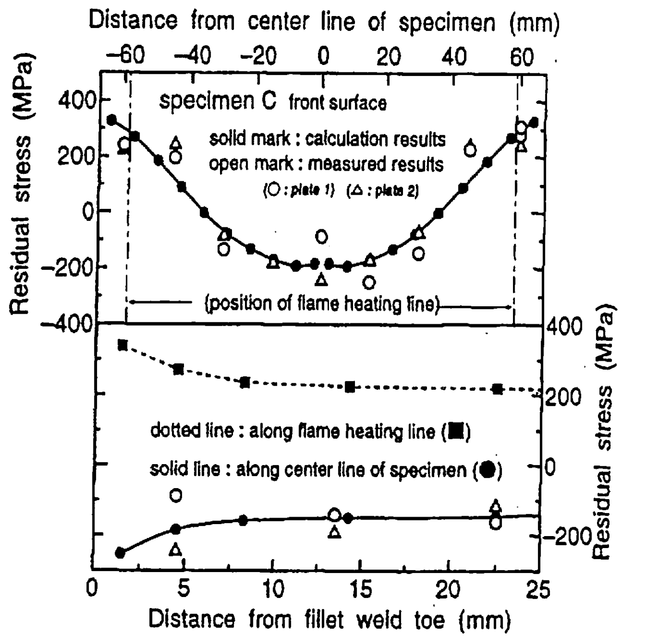

Fig. 10 Measured and calculated residual stress distributions on front surfaces of plate 1 and 2 for specimen C

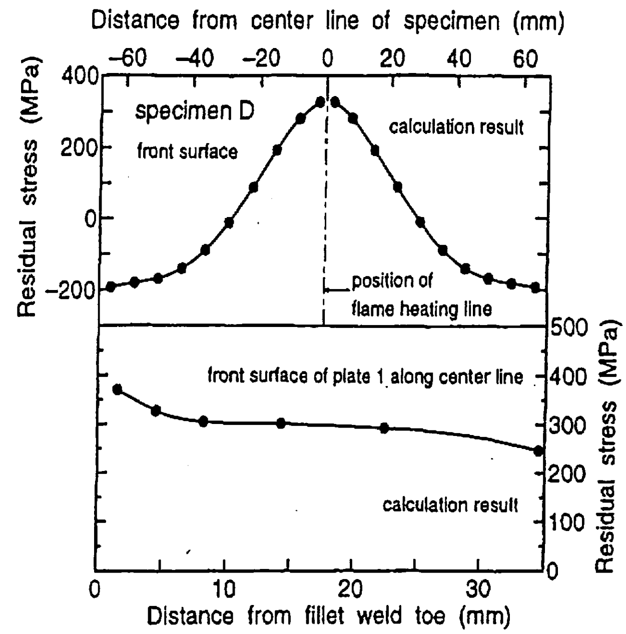

Fig. 11 Calculated residual stress distributions on front surfaces of plate 1 for specimen D

It is seen from former figures that residual stresses near the fillet weld toe at web position was about 350 [MPa] for specimen B and specimen D, and about -50 [MPa] for specimen A. Therefore fatigue strength of specimen A was higher than that of specimen B which had almost the same igue strength level as specimen D.

On the other hand, fatigue cracks initiated from fillet weld toe not only at web position but also at gas heating positions for specimen C. It is recognized from fracture surfaces that the fatigue crack from fillet weld toe at heated positions dominantly propagated in high cycle range and fatigue crack from fillet weld toe at gas heated position dominantly propagated in low cycle range. This shift of dominant cracked place could be naturally understood from the fact that the effect of residual stress on strain gradually disappear when applied stress increases.

Though stress concentration at fillet weld toe at the line heated position was less than that at fillet weld toe at web position, residual stress at the line heated position was higher than that at web position as shown in Fig.10. As a result, dominant fatigue cracked place was considered to shift from web position to line heated position as the maximum applied stress decreased. If fatigue crack did not initiate from the line heated position by means of decreasing stress concentration, for example, due to toe dressing and so on, a very large improvement of fatigue strength can be expected in the same manner as for the boxing fillet welded joint (Toyosada and Yamaguchi, 1994). Figure 12 also shows that fatige strength of specimen C is higher than one of specimen B in spite of decreasing the enhancement effect of fatigue strength after the shifting of the dominant cracked place. Considering that specimen B was constructed by the standard welding sequence of double bottom structures, gas heating which decreases the residual stress at stress concentration part is effective method for increase in fatigue strength of welded build-up structures in the same manner as for the above mentioned boxing fillet welded joint.

Figure 13 shows $S-N$ diagrams plotted against hot spot stress range at dominated crack propagating position. It is seen that hot spot fatigue strength level can be classified only by residual stress level at dominantly crack propagated position. Then it is understood that hot spot stress is an effective parameter in discussing the effect of stress concentration on fatigue strength.

A noticeable result in Fig.13 is that specimen A in which residual stress distribution was in Fig.8 shows the

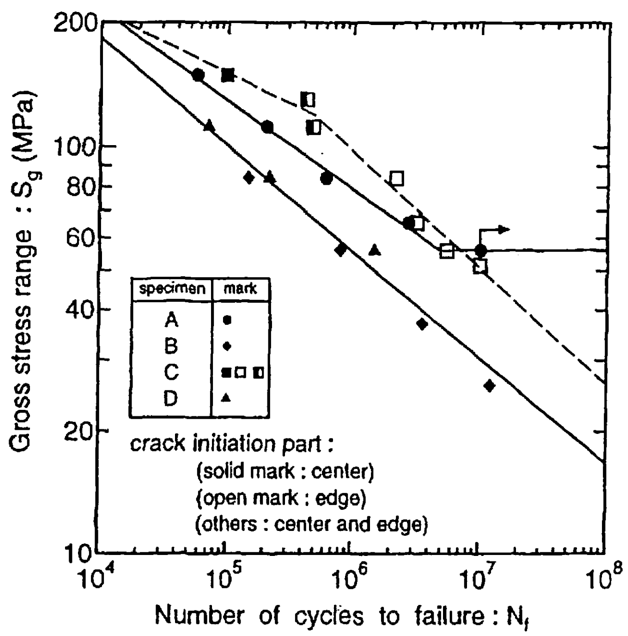

Fig. 12 S-N diagrams based on gross stress range

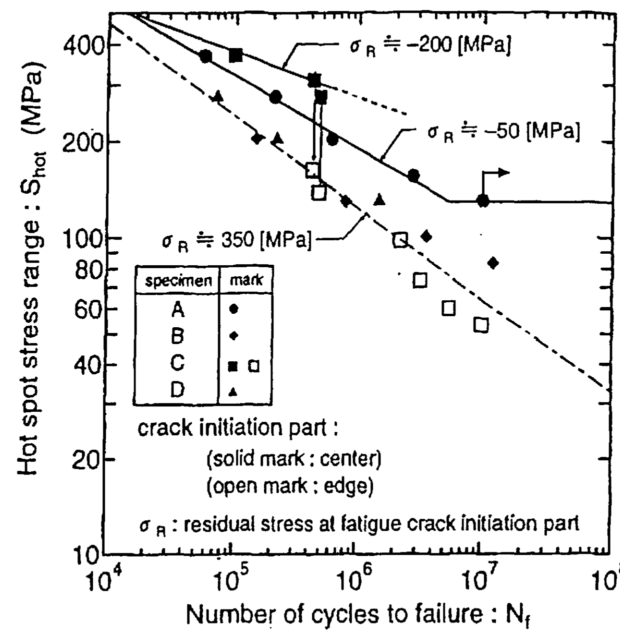

Fig. 13 S-N diagrams based on hot spot stress range

high level fatigue limit. This result might come from the fact that there is no large residual stress along the weld toe at which fatigue cracks may occure.

Therefore it is concluded that fatigue strength of welded structural elements can be improved by adopting an appropriate welding sequence, although it is difficult to choose the best welding sequence or by adopting an adequate line heating after welding. However, the effect of the welding sequence on residual stress can be assessed by the indicated method here.

CONCLUSION

It has been investigated that the effect of the welding sequence on residual stress distribution and fatigue strength and that the fatigue strength enhacement effect by changing tenslie residual stress into compressive one in the fatigue crack initiation region. The following results were obtained.

- By using parameter κ which is a coefficient expressing the effect of former stresses, it can be calculated that the residual stress distribution which was generated by multi-layer welding.
- Fatigue strength can be enhanced by choosing an adequate welding sequence near the fatigue crack initiation part.

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