Study on shot peened residual stress distribution under cyclic loading by numerical analysis*

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To prevent stress corrosion cracking or to extend the fatigue life of structures, various peening techniques are employed. In this research, to reproduce the residual stress distribution after shot peening, the residual stress due to multi-pass welding was predicted and the analysis of shot peening considering the welding residual stress distribution was conducted using the analysis system proposed by the authors, which was based on high-speed non-linear FE analysis method named Idealized Explicit FEM. The analyzed residual stress distribution due to the shot peening was compared with the experimental measurement using X-ray diffraction. As a result, it was found that the predicted residual stress distribution well reproduces the residual stress distribution after shot peening. To evaluate the effect of shot peening under the various loading conditions, tensile and compressive cyclic load was applied to the pipe joint on the numerical analysis considering the residual stress after shot peening. As a result, it was found that the influence of tensile cyclic load on the residual stress distribution is small while the compressive residual stress due to peening is decreased by the compressive cyclic load in the targeted pipe joint.

Key Words: Shot peening, Multi-pass welding, Residual stress, Nonlinear FE analysis, Cyclic load

1. Introduction

Residual stress is one of the main factors of fatigue crack and stress corrosion cracking (SCC) and it has a significant effect to the structural integrity. To ensure the structural integrity, it is important to investigate the residual stress distribution in advance. In the production of steel structures, welding is widely utilized and the residual stress inevitably introduced. To improve the residual stress distribution after welding, various peening techniques are proposed such as laser peening, shot peening, water jet peening and so on1-2). In these techniques, a compressive residual stress is introduced by applying the impulsive compressive load to the target surface, and the residual stress distribution on the surface will be improved. To discuss the effect of peening, various investigations have been carried out1-4). However, to investigate the effect of peening on fatigue crack or SCC, the change of residual stress distribution on the operation is more important.

To predict the residual stress distribution after shot peening, the authors have proposed an analysis system5). In this analysis system, collision of a shot is modeled by the equivalent load model and numerous numbers of collisions is considered. To predict the residual stress distribution after shot peening, the collision must be considered for the entire target surface. This may increase number of elements in FE analyses and the computational time can be unrealistic using the conventional analysis method. So, in this analysis system, a high-speed large scale non-linear analysis method named Idealized Explicit FEM is employed. By using this analysis system, it was shown that the residual stress distribution in the multi-pass welded pipe joint after the shot peening can be predicted within 10 days while it takes 10 hours to simulate the collision of a single shot using the conventional method. It was also shown that the predicted residual stress distribution and the measured residual stress by X-ray diffraction are in good agreement.

In this research, to investigate the persistence of the modification of residual stress distribution due to shot peening, the change of residual stress distribution in the multi-pass welded pipe joint is discussed under various load conditions considering the residual stress distribution after shot peening predicted by the proposed analysis system. For the load conditions, cyclic axial loads for both tension and compression, which assume a large earthquake, are considered and the influence of these loading conditions on the modified residual stress distribution due to shot peening is discussed numerically using 3-dimensional non-linear FE analysis.

2. Residual stress distribution of multi pass welded pipe joint after shot peening

2.1 Analysis model and conditions

Before investigating the influence of the load on the shot peened residual stress distribution, residual stress due to the
<s>multi-pass welding is predicted. Considering the predicted welding residual stress distribution, the residual stress distribution modified by shot peening is predicted using the analysis system proposed by the authors. The analysis model is shown in Fig. 1. The analysis model is meshed with hexahedral elements and the number of nodes and elements are 3,494,600, 3,004,664, respectively. The temperature dependent material properties of pipe (SUS316L) and weld metal (Y316L) are assumed as Figs. 2 and 3. The material of shot is assumed as SUS304. The isotropic hardening rule is employed as a work hardening model. In the analysis of welding residual stress, the anneal temperature is set to be 800 °C and equivalent plastic strain in an element, which has higher temperature than the anneal temperature, is set to zero to eliminate the effect of work hardening. The welding is carried out for 10 layers and each layer is welded by 1 pass. The welding conditions are as follows; current is 180 A, voltage is 10 V, welding speed is 10 cm/min and heat efficiency is 0.8. The condition of shot peening is as follows; initial velocity of shot is 60 m/s, shot radius is 0.8 mm. In the preparation of test specimen, the shot peening is carried out after cutting work of the inner and outer surface and is continued until the coverage reaches to 200%. In the analysis, the shot peening is carried out after removing the inner and outer removal part and is continued until the collision area ratio, which is the similar meaning of the coverage and defined in the literature5), reaches to 50. The effect of cutting work is not directly modelled in the analysis since the affected layer due to cutting is smaller than that of shot peening8).

2.2 Analysis result

Figure 4 shows the analyzed residual stress distribution after the shot peening on the cross section 180° from the start point of welding. In Fig. 4, (a) and (b) show the residual stress in axial direction $\sigma_z$ and hoop direction $\sigma_\theta$, respectively. From the figure, it is shown that the shot peened outer surface has a high compressive stress in both axial and hoop direction. Figure 5 shows residual stress distribution on the line A-A' defined in</s>
multi-pass welding is predicted. Considering the predicted hardening rule is employed as a work hardening model. In the welding residual stress distribution, the residual stress distribution with welding speed is 10 cm/min and heat efficiency is 0.8. The analysis of welding residual stress, the anneal temperature is set to 800 °C.

The analysis model is meshed with hexahedral elements and the number of nodes and elements are 3,494,600, 3,004,664, respectively and each layer is welded by 1 pass. The welding is assumed as Figs. 2 (b) Zoomed view of weld part.

2.2 Analysis result

It is shown that the shot peened outer surface has a high compressive stress in both axial and hoop direction. Figure 5 shows residual stress distribution on the line A-A’ defined in the literature), reaches to 50. The effect of cutting work is not directly modelled in the analysis since the affected zone of shot peening is carried out after cutting work of the inner and outer removal part and is continued until the coverage reaches to 200%.

In Fig. 4, (a) and (b) show the residual stress in axial and hoop direction can be seen. From the figure, (a) shows the stress distribution at the 1st peak tension, (b), (c) and (d) show those after 1st cycle, 2nd cycle and 3rd cycle, respectively. And the scale of deformation is 20. In the figure, (a) shows the stress distribution obtained in the previous chapter. The applied cyclic tension is as shown in Fig. 6. As shown in the figure, at first, the axial tension is applied as a forced displacement on the both axial end faces until the applied strain reaches 1%. This means the pipe is elongated to 1% for its axial length. After that, the 1% of compressive forced displacement is applied. These processes are iterated for the 3 times.

Figure 7 shows the obtained stress distribution on the cross section 180° from the start point of welding with deformation. The scale of deformation is 20. In the figure, (a) shows the stress distribution as those at as-peened is obtained in the shot peened base metal. It can be assumed that large equivalent plastic strain is introduced in the shot peened base metal and the high tensile stress is generated in the whole region at the peak tension. Especially, the highest tensile stress is found in the shot peened base metal. It can be assumed that large equivalent plastic strain is introduced in the shot peened base metal and the high tensile stress is generated due to the work hardening. After the 1st load cycle, compressive stress is generated and the similar stress distribution as those at as-peened is obtained in the shot peened region (Fig. 7 (b)). From Figs. 7 (c), (d) is found that

3. Change of residual stress distribution due to axial loads

3.1 Influence of tensile load

To discuss the effect of tensile load on the residual stress distribution after the shot peening, axial cyclic strain is applied to the multi-pass welded pipe joint shown in Fig. 1 considering the residual stress distribution obtained in the previous chapter. The applied cyclic tension is as shown in Fig. 6. As shown in the figure, at first, the axial tension is applied as a forced displacement on the both axial end faces until the applied strain reaches 1%. This means the pipe is elongated to 1% for its axial length. After that, the 1% of compressive forced displacement is applied. These processes are iterated for the 3 times.

Figure 7 shows the obtained stress distribution on the cross section 180° from the start point of welding with deformation. The scale of deformation is 20. In the figure, (a) shows the stress distribution on line A-A’ for each tensile load cycle. In the figure, the black dotted line shows the as-machined residual stress distribution, the green solid line shows that for the as-peened, the red solid line shows that for the 1st tensile peak, and the blue dotted line, broken line and solid line show that for the 1st, 2nd and 3rd load cycle, respectively. From Fig. 7 (a), it can be seen that high tensile stress is generated in the whole region at the peak tension. Especially, the highest tensile stress is found in the shot peened base metal. It can be assumed that large equivalent plastic strain is introduced in the shot peened base metal and the high tensile stress is generated due to the work hardening. After the 1st load cycle, compressive stress is generated and the similar stress distribution as those at as-peened is obtained in the shot peened region (Fig. 7 (b)). From Figs. 7 (c), (d) is found that
almost the same stress distribution as that for the 1st cycle is generated after the 2nd and 3rd load cycle and the stress in the peened region slightly increases. The plastic deformation is newly introduced to the peened surface and this would lead to the work hardening and increase of yield stress.

As shown above, the influence of tensile cyclic load on the shot peened residual stress distribution in the multi-pass welded pipe joint is investigated using elastic plastic analysis. The result indicated that the effect of cyclic tensile load is small on the targeted pipe joint.

### 3.2 Influence of compressive load

In the same way as the tensile cyclic load shown in the previous section, axial compressive cyclic strain is applied to the multi-pass welded pipe joint considering the shot peened residual stress distribution. The applied cyclic compression is as shown in Fig. 9. The applied compressive strain is -1% and the number of load cycle is 3.

Figure 10 shows the stress distribution on the compressive cyclic loading in the same way as Fig. 7. From Fig. 10 (a), the opposite bending deformation as the tensile loading (Fig. 7 (a)) can be seen at the peak compression. This is considered as the same mechanism as in the tensile cyclic loading; the difference of yield stresses between base metal and weld metal. Figure 10 (b) indicates that the tensile stress is generated just after the 1st load cycle. From Figs. 10 (c) and (d), it is also found that the tensile stress on the peened surface increases with the increase of applied compressive load cycles.

Figure 11 shows the distribution of stress in axial direction \( \sigma_z \) along line A-A' in the same way as Fig. 8. From this figure, it can be also seen that the compressive residual stress decreases in the peened region due to the compressive loading and almost the whole peened region has the tensile stress after the 3rd load cycle.

Figure 12 shows the distribution of plastic strain increment in axial direction \( \Delta \varepsilon_z \) newly introduced in each load cycle along line A- A’. From the figure, it is found that large compressive plastic strain is generated in the not-peened region at the 1st peak compression. However, the increment of plastic strain is less than applied strain of 1% and the plastic strain increment near the peened region (30mm from welding line) is less than that in the other not-peened region. The mechanism of this tendency can be considered as follows; a tensile force is generated on the outer surface by the bending deformation due to the difference of yield stresses between weld metal and base metal, and this decreases the plastic strain. After the 1st load cycle, tensile load is applied and tensile plastic strain is introduced while the plastic strain distribution keeps its tendency. As a result of the tensile load after the compression, tensile plastic strain is introduced in the not-peened region of base metal although the compressive load cycle is applied.

In the peened region, large compressive plastic strain is given in normal direction by the impulsive force normal to the surface due to peening and this causes tensile plastic strain in horizontal direction. This can be considered as a reason of the compressive

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**Fig. 8** Distribution of stress in axial direction \( \sigma_z \) along line A-A’ on tensile load cycle.

**Fig. 9** Schematic illustration of compressive cyclic load.

**Fig. 10** Distribution of stress in axial direction \( \sigma_z \) on compressive load cycles.

**Fig. 11** Distribution of stress in axial direction along line A-A’ in the same way as Fig. 8.

**Fig. 12** Distribution of plastic strain increment in axial direction newly introduced in each load cycle along line A- A’.
stress after peening. As shown above, in this investigation, the tensile plastic strain is introduced near the peened region by the compressive load cycle, and it can be assumed that the effect of the tensile plastic strain due to peening is canceled by the tensile plastic strain near the peened region and the compressive residual stress decreases. In addition, from Fig. 12, it is found that the generation of tensile plastic strain is continued after the 2nd cycle. Due to this, the compressive stress is decreased after the 2nd cycle by the same mechanism. These tendencies are similar as shown in the literature\(^7\).

As shown in this section, the effect of peening may decrease by applying the compressive load cycle in this investigation unlike the behavior under the tensile load cycle. Therefore, it can be said that the compressive residual stress due to peening can be cancelled depending on the loading condition.

4. Conclusions

In this research, the residual stress distribution in the multi-pass welded pipe joint after the shot peening was predicted using the analysis system based on the Idealized Explicit FEM. The predicted residual stress distribution was compared with the experimental measurements by X-ray diffraction and the results indicated that the analysis system can reproduce the residual stress distribution after the shot peening. Considering the residual stress distribution after the peening, tensile and compressive cyclic load was applied and the effect of peening was numerically investigated. As a result, it was found that the influence of tensile cyclic load on the residual stress distribution is small while the compressive residual stress due to peening is decreased by the compressive cyclic load in the targeted pipe joint.

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