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Numerical Investigation on Persistence of Modified Residual Stresses Due to Shot Peening

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ABSTRACT

In this research, to investigate the persistence of compressive stress on a shot peened surface, the residual stresses in a multi-pass welded pipe joint after shot peening were analyzed. Then, the variation of the stress distribution in the welded pipe was examined by elastic plastic analyses under axial tension and compression with consideration of the shot peened residual stress distribution. As a result, it was found that the stress distribution remains in compression by applying tension followed by compression. It was also found that the compressive stress can decrease by applying compression followed by tension. From the above results, it can be said that the persistence of compressive stress due to shot peening should be discussed before the peening operation, especially a large load can be assumed to act on the shot peened part.

KEYWORDS

Shot peening, Residual stresses, Multi-pass welding, Elastic-plastic analysis, Finite element analysis

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1. Introduction

Welding can cause a high tensile residual stress to occur on the surface of a part. This residual stress affects the initiation of a fatigue crack and stress corrosion cracking (SCC) [1]. To improve the tensile residual stress on the surface due to welding, various peening techniques are commonly employed [2, 3]. In the peening process, an impulsive load acts on the target surface and the stress state on the target surface is improved.

The residual stress distribution after peening has been predicted in several reports [4, 5]. To investigate the residual stress distribution in weld joints after shot peening, the authors previously proposed an analysis system [6]. In the study, the reaction force under the collision of shot was modeled as the equivalent load model. Large numbers of shot collisions were considered in a large-scaled dynamic elastic plastic analysis in the previous research.

On the other hand, various loads act on shot peened structures under operation. Thus, it is important to discuss the persistence of the compressive stress introduced by shot peening. The effect of external force has been discussed in several reports [7, 8]. But, to the best of the author's knowledge, very few reports considered the shot peened residual stress distribution on the entire target surface.

In this research, to investigate the persistence of the stress distribution after shot peening under various load conditions, the proposed analysis system [6] is applied to the prediction of residual stresses in a multi-pass welded pipe joint after shot peening. After that, with the obtained residual stress distribution, the variation of the stress distribution is investigated by conducting elastic plastic analyses. Through these investigations, the importance of prior assessment for the persistence of the residual stress distribution after shot peening is discussed.

2. Analysis System of Residual Stress Distribution After Shot Peening

In shot peening, 1 mm or smaller shots collide with the target surface numerous times and

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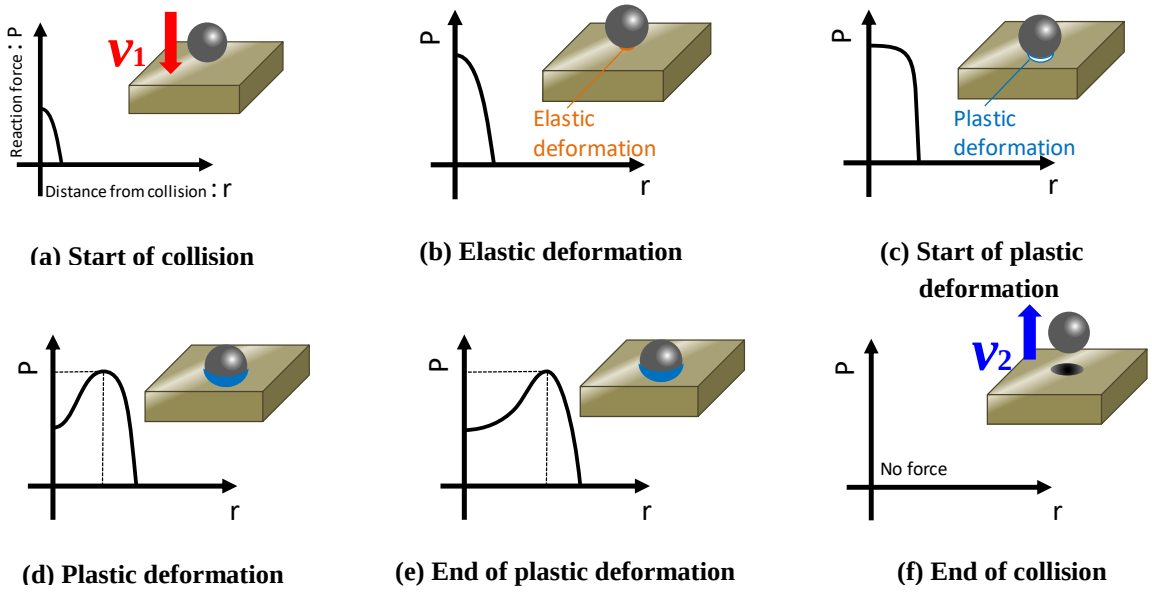


(a) Start of collision (b) Elastic deformation (c) Start of plastic deformation

(d) Plastic deformation (e) End of plastic deformation (f) End of collision

Fig. 1. Schematic illustration of equivalent load model for shot collision

compressive stress is introduced. The authors previously proposed an analysis system that can predict the residual stress distribution after shot peening by using the large-scale nonlinear mechanical analysis method named Idealized Explicit FEM [6] together with the parallelization on a graphics processing unit (GPU) [9]. In this research, the proposed analysis system is applied to the prediction of the residual stress distribution after shot peening.

In dynamic elastic plastic analyses using Idealized Explicit FEM, the semi-discretized equation of motion by FEM is discretized for time by using Newmark's beta method and the linearized equation shown in Eq. (1) from the Newton-Raphson is used as fundamental equation:

$$[K_{eff}]\,{}^{(k)}\{\Delta U\} = {}^{(k)}\{F_{eff}\} \tag{1}$$

where $[K_{eff}]$, $\{\Delta U\}$, and $\{F_{eff}\}$ are the effective stiffness matrix, the displacement increment vector, and the effective load vector, respectively. The left superscript (k) is the iteration number in the Newton-Raphson method. The details of each term is shown in the reference [10].

Adding the virtual inertial term and the virtual damping term yields the following equation:

$$[M_{dum}]\{\ddot{U}_{dum}\}_{\tau} + [C_{dum}]\{\dot{U}_{dum}\}_{\tau} + [K_{eff}]\{U_{dum}\}_{\tau} = \{F_{eff}\} \tag{2}$$

where $[M_{dum}]$ and $[C_{dum}]$ are the virtual mass matrix and the virtual damping matrix, respectively. $\{\ddot{U}_{dum}\}$, $\{\dot{U}_{dum}\}$, and $\{U_{dum}\}$ are the acceleration vector, the velocity vector, and the displacement vector at virtual time τ, respectively. The displacement vector is defined as $\{U_{dum}\} = \{\Delta U\}$.

Discretizing Eq. (2) by the central difference and advancing the time steps until the virtual inertial term and the virtual damping term become negligibly small, that is, advancing the virtual time τ in Eq. (2). The displacement vector obtained by advancing the virtual time τ is used as a solution. By using these steps, it is expected that the same solution as that by solving Eq. (1) can be obtained. The virtual mass and damping matrix ($[M_{dum}]$ and $[C_{dum}]$) are utilized only to obtain the converged solution. The formulation of these matrices to reduce the time steps for convergence, are employed as shown in [6].

A load on the collision of a shot is considered in the above dynamic elastic plastic analysis method. As shown in Fig. 1, the history of the load distribution during the collision of a shot is modeled as an equivalent load model, which is introduced as an external force [6].

In addition, the persistence of the compressive stress introduced by peening is investigated by conducting elastic plastic analyses after shot peening. Therefore, the following series of analyses are conducted in this research. First, welding residual stresses are predicted by thermal elastic plastic analysis. Subsequently, shot peening process is analyzed by the abovementioned analysis system. Finally, the variation of the stress distribution after shot peening is obtained by elastic plastic analysis.

3. Prediction of Residual Stress Distribution After Shot Peening

3.1. Analysis model and conditions

Figure 2 (a) shows the entire model. The detail of the welded part is shown in Fig. 2 (b). Welding is carried out in 1 pass for each layer for a total of 10 passes. The welding condition is as follows: current 180 A, voltage 10 V, and speed 1.33 mm/s. The heat efficiency is assumed as 80%. The assumed temperature dependent material properties are shown in Figs. 3 and 4. The anneal temperature is assumed as 850°C where stress relief heat treatment of austenitic steel is conducted [10]. The effect of work hardening at high temperature is eliminated by setting the equivalent plastic strain to zero [11].

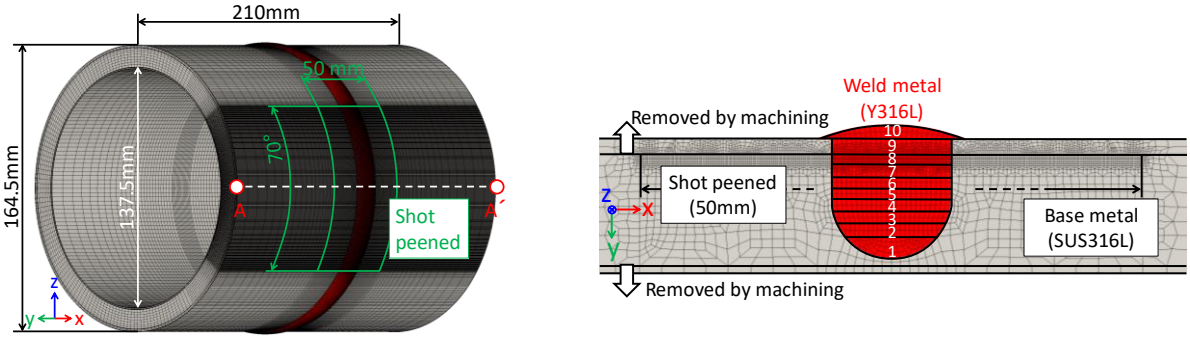
After the welding, the inner and outer surfaces are removed by machining. This process is modeled by disabling elements in the removal region. The redistribution of stress is analyzed by the static elastic plastic analysis.

The target of shot peening is the region 25 mm left and right of the welding line and up to 70° around the point 180° from the start point of welding. The target surface of shot peening is meshed with hexahedral elements of 0.2 mm and the numbers of elements and nodes are 3,004,664 and 3,494,600, respectively. The radius of a shot is 0.8 mm and the projection velocity is set to 60 m/s. The analysis of shot peening continues until the collision area ratio Rc reaches 50. Rc is the ratio of the sum of the loaded area by the equivalent load model to the target area [6].

In the above analysis, the following computer is employed: CPU is an Intel Core i7 3.5 GHz processor, RAM is 128 GB, GPU is an NVIDIA GeForce GTX TITAN X processor.

3.2. Analysis results

Figure 5 shows the residual stress in axial direction (σ_x) distribution after welding on the cross section 180° from the start point of welding. The figure indicates that large residual stress occurs due to welding. Figure 6 and 7 show the axial stress distribution after shot peening of the entire pipe and



(a) Entire model **(b) Zoomed view of welded part**

Fig. 2. Analysis model for multi-pass welded pipe joint

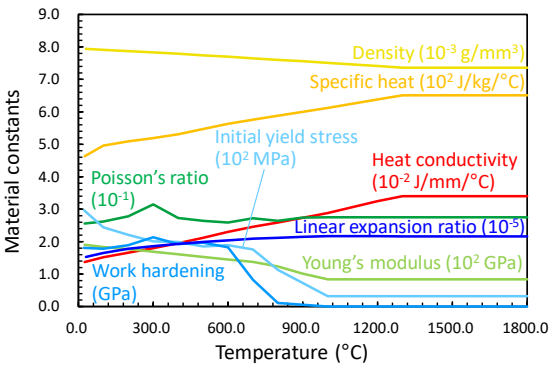


Fig. 3. Temperature dependent material constants of SUS316L (base metal)

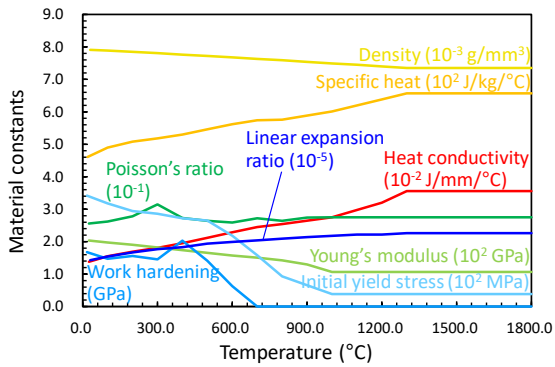


Fig. 4.Temperature dependent material constants of Y316L (weld metal)

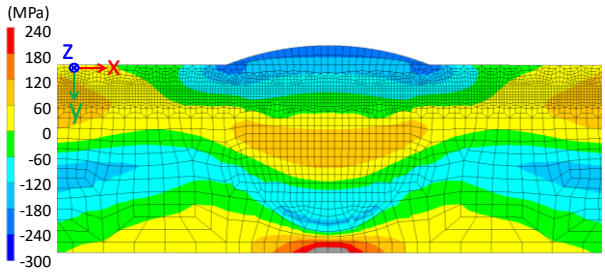


Fig. 5. Axial residual stress distribution after welding on the cross section at 180° from the start of welding

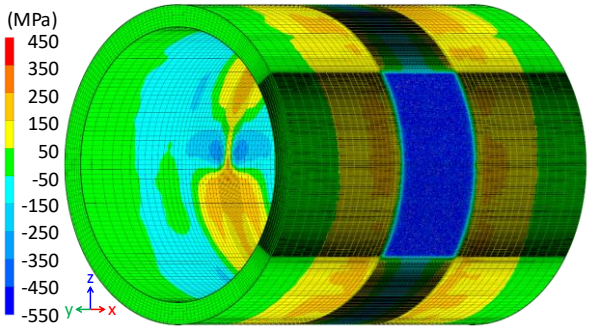


Fig. 6. Axial stress distribution after shot peening

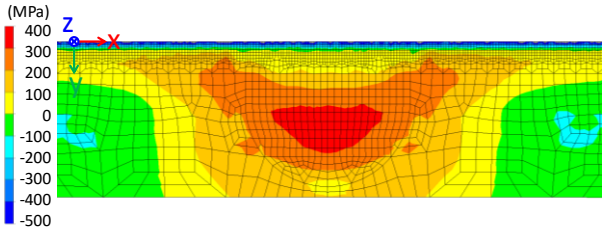


Fig. 7. Axial residual stress distribution after shot peening on the cross section at 180° from the start of welding

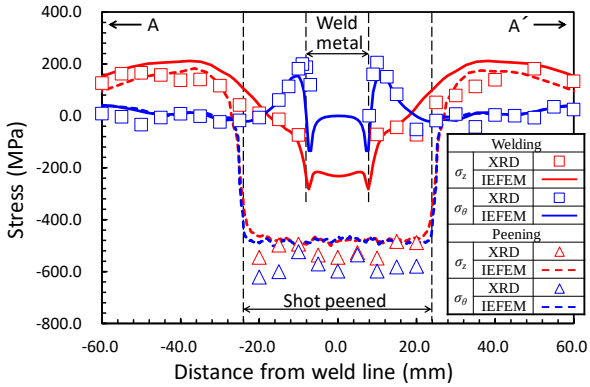


Fig. 8. Comparison of analyzed and measured residual stress distribution after welding and shot peening

that on the same cross section, respectively. From these figures, it is found that strong compressive stress is introduced to the target surface.

Figure 8 shows the comparison of the residual stress distribution measured by XRD and calculated by the analysis. Figure 8 shows that the analyzed axial and hoop residual stress distributions agree well with those measured by XRD after both welding and shot peening.

As shown here, the stress distribution predicted by using the proposed analysis system can reproduce the measured results well. The computing time of was about 10 days in total.

4. Variation of Residual Stress After Shot Peening due to Various Loads

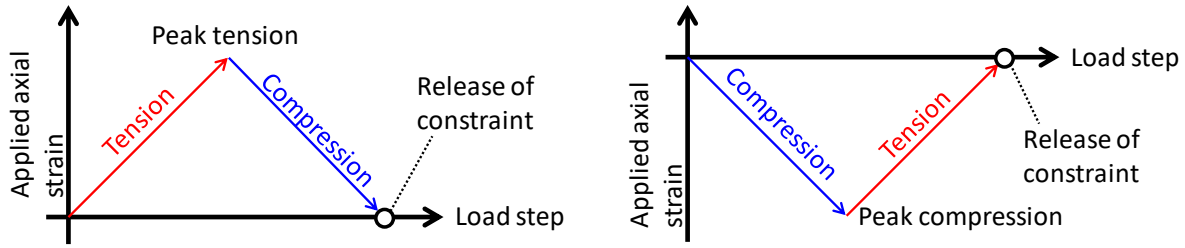
4.1. Analysis model and conditions

To investigate the persistence of the compressive stress introduced by shot peening, the variation of the stress field is discussed by applying external loads to the multi-pass welded pipe model after shot peening. The analysis model and material properties are the same as those given in Section 3.

Figure 9 schematically shows the two cases of load conditions in this analysis. In Fig. 9 (a), a tension is applied; after that, the same quantity of compression is given, and then the constraint is released. This case is defined as the tension-compression-release condition. Likewise, the compression-tension-release condition (Fig. 9 (b)) is also investigated. Four cases of applied tensile/compressive strain are assumed: 0.15%, which is assumed to be within the elastic deformation; 0.5% and 0.7%, which exceed the yield stress; and 1.0%, which assumes excessive loads such as great earthquakes.

4.2. Influence of tensile load

Figure 10 shows the deformed shape during tensile deformation with the axial stress distribution at 1.0% tension. The deformation in this figure is magnified by ten times. The barrel-shaped deformation is obtained by applying tension. The reason for this deformation is assumed as follows. The yield stress



(a) Tension-compression-release condition **(b) Compression-tension-release condition**

Fig. 9. Schematic illustration of loading conditions

of the weld metal is higher than that of the base metal. Thus, the deformation in the weld metal is smaller than that in the base metal and the axial elongation due to tension becomes different. It can be assumed that this difference can cause the bending deformation along axial direction and the barrel shaped deformation.

Figure 11 shows the axial stress distribution under the applied tension on the cross section at 180° from the start point of welding. The tensile stress occurs over the entire cross section at the peak tension, as shown in (a). This is because the large 1.0% tensile strain is applied. In the case that the compressive strain is applied after the tension (b), almost the entire cross section has compressive stress. After the release of the compressive strain (c), the strong compressive stress in the shot peened part recovers.

Figure 12 shows the axial stress distribution along line B-B′ after the tension-compression-release condition. Figure 13 shows the distribution of the plastic strain increment along line B-B′ after loading under the tension-compression-release condition. The effect of first applying the tension remains at

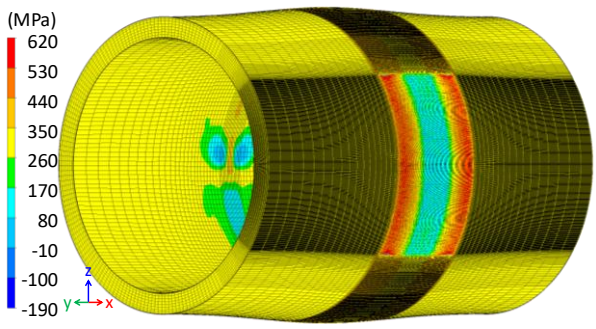
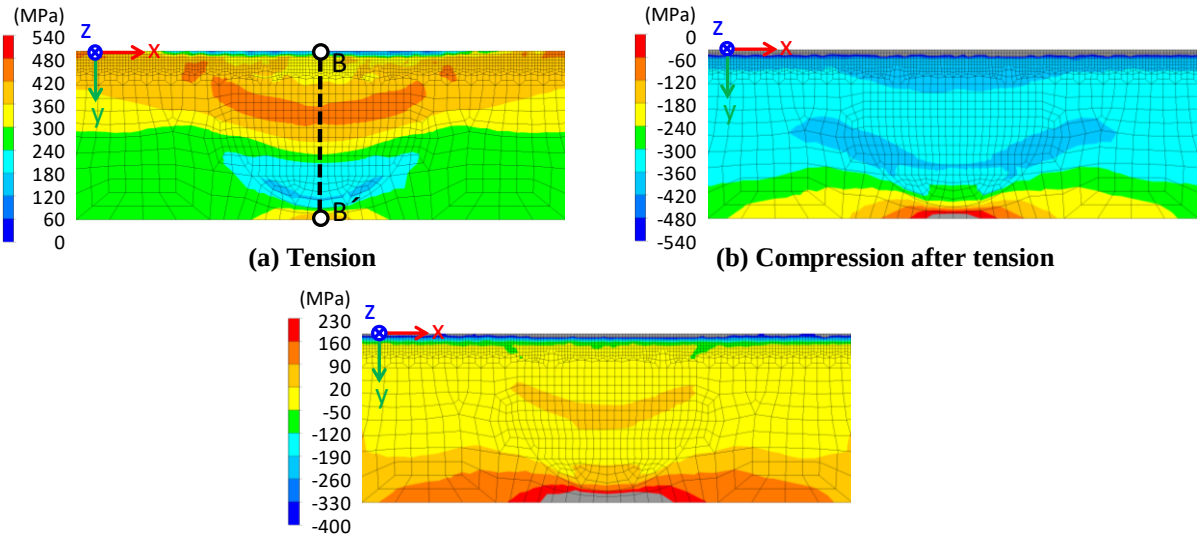


Fig. 10. Deformed shape of pipe joint and axial stress distribution during tensile deformation



(a) Tension **(b) Compression after tension**

(c) Release after tension and compression

Fig. 11. Distribution of stress in axial direction

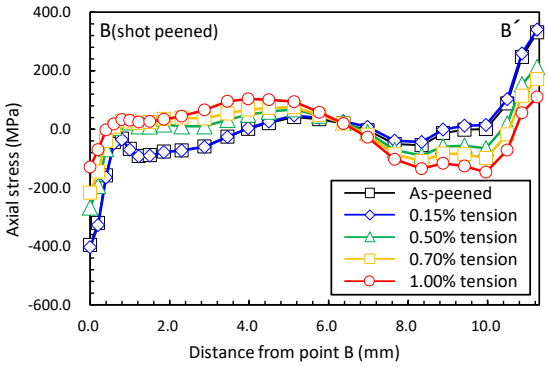


Fig. 12. Comparison of axial stress (σ_x) under tension-compression-release condition

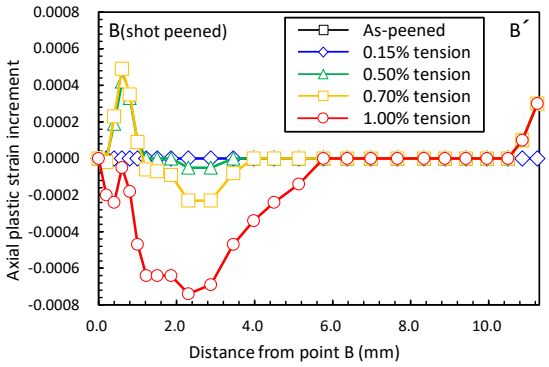


Fig. 13. Comparison of plastic strain increment under tension-compression-release condition

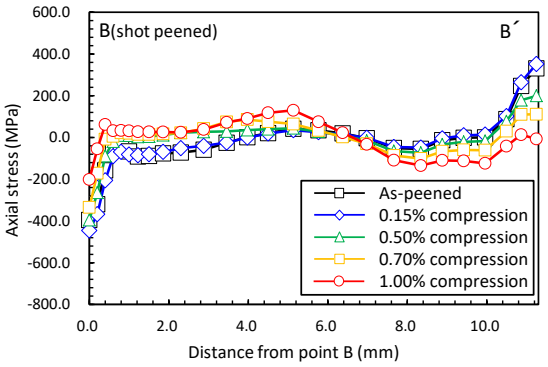


Fig. 14. Comparison of axial stress (σ_x) under compression-tension-release condition

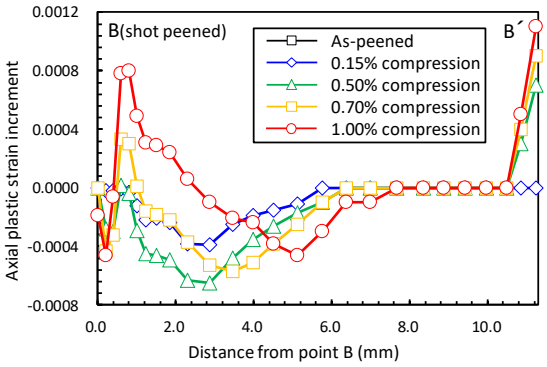


Fig. 15. Comparison of plastic strain increment under compression-tension-release condition

0.50% tensile strain and the compressive stress slightly decreases. In the case of 0.70% tensile strain, the compressive plastic strain increment is larger than that at 0.50% tensile strain, and that is even larger at 1.0% tensile strain. Especially, at 1.0% tensile strain, large compressive plastic strain is generated. The compressive stress on the shot peened surface increases due to the increase of compressive plastic strain.

In summary, in the case that the compression is applied after applying tension, the effect of tension decreases and the compressive stress in the shot peened surface can be maintained.

4.3. Influence of compressive load

In the same way as the tension-compression-release condition, the variation of the stress distribution is investigated in the case that the load conditions shown in Fig. 9 (b) is applied.

Figures 14 and 15 show the axial stress distribution and the axial plastic strain increment under the compression-tension-release condition, respectively. For the conditions over the applied compressive strain of 0.7%, the tensile plastic strain is pronouncedly generated, and the compressive stress on the shot peened surface decreases. As shown here, it can be assumed that the compressive stress introduced by shot peening can decrease in case that the tension is applied after applying compression.

From these discussions of the numerical investigations, the compressive stress introduced by shot peening can maintain unless excessively large loads are applied in the targeted weld joint. Therefore, it can be said that the persistence of the compressive stress introduced by shot peening should be investigated in advance, especially in the case that large load acts on the peened part.

5. Conclusion

To numerically investigate the persistence of compressive stress on a surface due to shot peening,

this research analyzed the residual stress distribution of a multi-pass welded pipe joint after shot peening using the analysis system proposed by the authors. With the analysis results of the residual stress distribution, elastic plastic analyses were conducted under axial tension and compression, and the variation of the residual stress distribution after shot peening due to the load conditions was investigated. As a result, it was shown that the proposed analysis system can accurately simulate the residual stress due to welding and shot peening in realistic computing time. It was seen that the compressive stress introduced by shot peening can be maintained in the case that the compression is applied after the tension. It was also found that the compressive stress on the shot peened surface can maintain unless excessively large loads are applied in case that the tension is applied after the compression. These results indicated that to evaluate the persistence of the compressive stress due to shot peeing, it is important whether large loads acted to the part.

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