

# Sustainability of compressive residual stress by stress improvement processes

Satoru NISHIKAWA<sup>1,\*</sup> Shigeru OKITA<sup>2</sup> and Atsunori YAMAGUCHI<sup>3</sup>

<sup>1</sup> Japan Power Engineering and Inspection Corporation, 14-1 Bentencho, Tsurumi-ku Yokohama, 230-0044, Japan

<sup>2</sup> Japan Power Engineering and Inspection Corporation, 14-1 Bentencho, Tsurumi-ku Yokohama, 230-0044, Japan (Present address: The Japan Welding Technology Center)

<sup>3</sup> Japan Power Engineering and Inspection Corporation, 14-1 Bentencho, Tsurumi-ku Yokohama, 230-0044, Japan (Present address: Japan Society of Maintenology)

#### ABSTRACT

Stress improvement processes are countermeasures against stress corrosion cracking in nuclear power plant components. It is necessary to confirm whether a compressive residual stress induced by stress improvement processes can be sustained under operation environment. In order to evaluate stability of the compressive residual stress in 60-year operating conditions, the 0.07% cyclic strains of 200 times at 593 K were applied to the welded specimens, then a thermal aging treatment for  $1.66 \times 10^6$  s at 673 K was carried out. As the result, it was confirmed that the compressive residual stresses were sustained on both surfaces of the dissimilar welds of austenitic stainless steel (SUS316L) and nickel base alloy (NCF600 and alloy182) processed by laser peening (LP), water jet peening (WJP), ultrasonic shot peening (USP), shot peening (SP) and polishing under 60-year operating conditions.

#### **KEYWORDS**

Stress improvement processes, Sustainability of the compressive residual stress, Austenitic stainless steel, Nickel base alloy, LP, WJP, USP, SP, Polishing

ARTICLE INFORMATION

Article history: Received 15 January 2015 Accepted 19 August 2015

## 1. Introduction

One of the methods to prevent components of a nuclear power plant from stress corrosion cracking (SCC) is a stress improvement process such as peening techniques (laser peening, water jet peening, etc.) and polishing for applying compressive residual stress to a region where SCC is supposed to occur. However, when a compressive residual stress is applied for prevention of SCC, it is necessary to confirm persistence of the compressive residual stress upon the consideration of aged deterioration of the component.

Until now, many studies have been conducted to investigate persistence of a compressive residual stress. In these studies, the relaxation of a compressive residual stress were examined on the following conditions:

- ① Thermal relaxation by thermal aging treatment<sup>[1]-[4]</sup>
- ② Stress (strain) loading<sup>[1], [5]-[8]</sup>
- ③ Thermal relaxation by thermal aging treatment with stress (strain) loading<sup>[3], [5], [9]</sup>
- (4) Thermal relaxation by thermal aging treatment in the presence of welding residual stress<sup>[3], [4], [7]</sup>
- (5) Stress (strain) loading in the presence of welding residual stress<sup>[10], [11]</sup>
- 6 Thermal relaxation by thermal aging treatment in welding residual stress with stress (strain) loading<sup>[3], [12]</sup>

The examined materials are SUS304(Type304), SUS316L(Type316L), NCF600(UNS N06600),

<sup>\*</sup>Corresponding author, E-mail: nishikawa-satoru@japeic.or.jp



alloy132 and alloy182.

From the results of the studies, it was confirmed that a compressive residual stress is retained on each of the conditions (1-6), but a consensus opinion about persistence of a compressive residual stress has not been reached so far because the test condition and the specimen type were different for each stress improvement process.

In this study, we investigated persistence of a compressive residual stress by performing stress relaxation tests under the same condition based on the environment of a nuclear power plant using specimens of the same size as the specimens were treated with different stress improvement processes; laser peening (LP), water jet peening (WJP), ultrasonic shot peening (USP), shot peening (SP) and polishing.

# 2. Experimental procedure

#### 2.1. Preparation of evaluated specimens

Table 1 shows the chemical composition of each material prepared for making the dissimilar welded joints used in stress relaxation tests as the specimens. Figure 1 shows the schematic of these dissimilar welded joints. The two base metals SUS316L and NCF600 were joined by shielded metal arc welding with the weld metal Alloy182 to form the dissimilar welded joints of 15 mm in thickness, 200 mm in width and 250 mm in length. When the welding was performed, the electrode was connected to the positive terminal of a direct current power source. The current was set to 110-140 A. The welding speed was set to 2.0–4.1 mm/s. The weld was made in five layers with nine passes. The electrode was moved carefully not to form electrode stop/start points around the center of the specimens, where residual stress would be evaluated. The surface of the welded joints was made flat by mechanically grinding the weld reinforcement, and the plate thickness was made 12.1 mm by mechanically grinding the surface of the initial layer side. The evaluated specimens (12.1 mm in thickness, 45 mm in width and 180 mm in length) were cut out from the welded joints in such a way that the weld line was located along the center line in the longitudinal direction of the specimens. The final layer side of the specimens was electrolytically polished by more than 0.1 mm in order to remove the machined layer of the surface. The stress improvement processes were performed on a 40 mm×45 mm area of the electrolytically polished surface of the specimens as shown in Figure 2. The stress improvement processes performed were LP, WJP, USP, SP and polishing. Table 2 shows the conditions of LP, WJP, USP and SP. In the following sections, the effects of these stress improvement processes on the persistence of the compressive residual stress are described.

									-				
Material	С	Si	Mn	Р	S	Ni	Cu	Cr	Fe	Мо	Nb+Ta	Ti	Others
SUS316L	0.015	0.66	1.21	0.035	0.003	12.24	-	17.41	Bal.	2.08	-	Ι	-
NCF600	0.08	0.23	0.25	0.008	0.001	73.54	0.07	16.77	9.05	-	-	-	-
Alloy182	0.058	0.76	7.38	0.007	0.004	68.3	0.03	14.30	7.08	Ι	1.52	0.37	<0.50

Table 1 Chemical composition of the base metal and the deposited metal used (mass%)



Figure 1 Schematic of a dissimilar welded joint from which specimens for the sustainability evaluation of compressive residual stress were cut





Figure 2 Schematic of peened and polished area on the specimen

LP	Pulse energy	60 mJ				
	Spot diameter	0.7 mm				
	Number of pulses	7000 pulse/cm² (SUS316L)				
	Number of pulses	1800 pulse/cm <sup>2</sup> (NCF600, alloy182)				
WJP	Injection quantity	800 cm³/s				
	Injection time	24 s/cm				
	Injection distance	140 mm				
	Injection angle	90 °				
	Nozzle diameter	2 mm				
USP	Amplitude	50 <i>µ</i> m				
	Ball diameter	4 mm				
	Projection time	150 s				
SP	Material of cut wire	SUS304				
	Cut wire contour	$\phi$ 0.8 mm × 0.8 mmL				
	Projection angle	90 °				

Table 2 Conditions of the LP, WJP, USP and SP

#### 2.2. Strain loading

Strain was applied multiple times to the specimens in order to evaluate the influence of the stress variation due to the plant start/stop operations. The yield stress of SUS316L, NCF600 and alloy182 decreases with the increasing temperature<sup>[12]</sup>. Therefore, the loading with the operating temperature and the stress occurred at the start-up of a nuclear power plant should be severe condition for the relaxation of the compressive stress. Because applying a 0.07% strain at the PWR operating temperature 593 K provides a stress equal to or more than the stress arising in the start-up of a plant, a 0.07% strain was cyclically applied to the longitudinal direction of the specimens at 593 K. The strain rate was set to  $6.67 \times 10^{-5}$  s<sup>-1</sup>. The strain profile was chopping wave. The number of strain loading of specimens were 200 times considered as the cycle number more than the design number assumed 60 years operation. In addition, operating temperature in the BWR power plant is at 563 K and the strain equivalent to the above is caused. It can be proposed that the compressive residual stress is sustained with these conditions.

#### 2.3. Thermal aging treatment

In addition to stress loading, thermal relaxation by a long term aged at operating temperature is considered as a factor of sustainability of compressive stress by a stress improvement process during plant operating. To examine the sustainability of the compressive residual stress considering both



operating temperature and stress loading, specimens were subjected to 200 cycles of strain and subsequent thermal aging treatment simulating the actual long-term operation. Assuming that PWRs are operated for 60 years at an operating rate of 100%, their components are subjected to a thermal history of 593 K for  $1.89 \times 10^9$  s. Using a Larson-Miller parameter, this condition is converted to an acceleration condition of 673 K for  $1.66 \times 10^6$  s, which is used in the thermal aging treatment in this study. The operating temperature of BWRs is 563 K, which is lower than that of PWRs. Therefore, if the compressive residual stress is sustained under the above acceleration condition, it will be sustained under the operating conditions of BWRs.

#### 2.4. Residual stress measurement

Specimens were subjected to 1, 2, 5, 10, 50, or 200 cycles of strain and subsequent thermal aging treatment. The residual stress of thus-obtained specimens was measured by X-ray diffraction. Table 3 summarizes the conditions for the measurement of residual stress by the  $2\theta - \sin^2 \varphi$  method.<sup>[14]</sup> The residual stress was measured at one point on each of SUS316L, NCF600, and alloy 182; however, measurement was carried out twice at the same point on alloy 182 in consideration of the variability of measured results. Figure 3 shows the measurement points of residual stress. The surface residual stress was measured at a position 2 mm from the fusion line in the heat-affected zone of SUS316L and NCF600 and at the center of alloy 182. According to the results obtained by Masaki<sup>[6]</sup>, the residual stress changes negligibly in the direction perpendicular to that of stress loading and is relaxed in the direction of stress loading. Therefore, the residual stress in the longitudinal direction of specimens was measured in this study. In addition, the surface of the specimens obtained after 200 cycles of strain and subsequent thermal aging treatment was subjected to electrolytic polishing, and the residual stress at a depth of 10–200 µm was measured to evaluate the sustainability of the compressive residual stress inside the specimens. For specimens subjected to stress improvement processes other than polishing (i.e., LP, WJP, USP, and SP), the residual stress was measured at depths of 100 and 200 µm for SUS316L and NCF600, respectively. For specimens subjected to polishing, the residual stress was measured at a depth of 10 µm for both SUS316L and NCF600 because polishing affects the compressive residual stress up to a depth of 50 µm<sup>[15]</sup>. As shown in Figure 3, the measurement point of the residual stress for the specimens after the thermal aging treatment was located symmetrical to those for the specimens obtained after 200 cycles of strain application because a concave was formed on the surfaces of SUS316L and NCF600 by electrolytic polishing.

Condition	SUS316L	NCF600	Alloy182		
Characteristic X–ray	Cr–Kβ				
Tube voltage ∕tube current		40 kV/30	mA		
Electrolytic polishing area	φ3	mm	—		
Osliimster ener	40	∮2 mm (Without WJP and LP)			
Collimator area	φΖ	∲4 mm (WJP and LP)			
Diffraction plane		311	•		
Diffraction angle $(2 \theta)$	148.5 °	153.6 °			

Table 3	Measure	ment cor	dition o	of residual	stress
	by X-ray	diffractio	n		



Measurement point of residual stress until 200 cycles of 0.07% strain
Measurement point of residual stress after thermal aging treatment
Figure 3 Schematic of measurement point of residual stress by X-ray diffraction



# 3. Results and discussion

#### 3.1. Sustainability of surface residual stress of SUS316L and NCF600

Figure4 shows the surface residual stress after 200 cycles of strain application and subsequent thermal aging treatment at measurement positions 2 mm from the fusion line on SUS316L and Ν С F 6 0 0 300 300 ▲SUS316L(As welded) ▲SUS316L(As welded) NCF600 (As welded) NCF600 (As welded) ∆SUS316L  $\triangle$  SUS316L Residual stress (MPa) Residual stress (MPa) 0 O NCF600 ONCF600 0 C 300 -300 0 Δ ۵ Ø A 0 Δ  $\triangle$ -600 -600 -900 -900 After thermal After thermal 0 1 10 100 0 10 100 aging treatment aging treatment 1 Number of strain cycles Number of strain cycles (a) (b) 300 300 ▲ SUS316L(As welded) ● NCF600(As welded) ▲SUS316L(As welded) NCF600 (As welded) ∆SUS316L  $\triangle$  SUS316L Residual stress (MPa) Residual stress (MPa) O NCF600 O NCF600 0 0 ∆ 0  $\triangle$  $\triangle$ 0 Ø 300 300 θ Ô 0 ₿ Ø -600 -600 -900 -900 After thermal After thermal 0 10 100 0 10 100 1 aging treatment 1 aging treatment Number of strain cycles Number of strain cycles (c) (d) 300 ▲SUS316L(As welded) NCF600 (As welded) ∆SUS316L Residual stress (MPa) O NCF600 0 -300 6  $\stackrel{\triangle}{_{\mathrm{O}}}$  $\stackrel{\triangle}{\rightarrow}$ Δ Δ 0 0 -600 -900 After thermal 0 1 10 100 aging treatment Number of strain cycles (e)

Figure 4 Effect of 200 cycles of 0.07% strain at 593 K and subsequent thermal aging treatment for 1.66  $\times 10^{6}$  s at 673 K on surface compressive residual stress in SUS316L and NCF600: (a) LP, (b) WJP. (c) USP. (d) SP. and (e) polishing



subjected to each stress improvement process. Although the surface residual stress was tensile owing to welding, it became compressive as a result of the stress improvement processes. The compressive residual stress was sustained on the surfaces of SUS316L and NCF600 subjected to all five stress improvement processes after 200 cycles of 0.07% strain application at 593 K and subsequent thermal aging treatment for  $1.66 \times 10^6$  s at 673 K. The compressive residual stress of many specimens was significantly relaxed after the first cycle of strain application and remained almost the same up to 200 cycles of strain application, although the tendency of relaxation differed depending on the stress improvement process used and the material. From this result, it was found that the compressive residual stress was significantly relaxed owing to the redistribution of stress resulting from the temperature increase and stress loading in the first cycle of strain application and that the change in the compressive residual stress was negligible upon subsequent stress loading.

#### 3.2. Sustainability of surface residual stress of alloy182

Figure 5 shows the surface residual stress after 200 cycles of stress application and subsequent thermal aging treatment at the center of alloy182 subjected to each stress improvement processes. The surface residual stress became compressive after any stress improvement process. The compressive residual stress was sustained on the surface of alloy182 after 200 cycles of 0.07% strain application at 593 K and subsequent thermal aging treatment for  $1.66 \times 10^6$  s at 673 K. Although the compressive residual stress was relaxed up to five cycles of strain application in the specimens subjected to WJP, it was approximately -500 MPa after ten cycles of strain application. The reason behind the significant change in the compressive residual stress of the specimens subjected to WJP compared with those subjected to other stress improvement processes is considered to be a large measurement error. The crystal grains in alloy182 are larger than those in the base material<sup>[15]</sup> and crystals solidify in the <100> direction. Thus, the number of crystal grains included in the X-ray irradiation region decreases, so that accuracy of X-ray stress measurement decreased. Therefore, in the specimens subjected to WJP with a small area of surface processing<sup>[16]</sup>, large crystal grains remain, leading to a large measurement error and the large change in the compressive residual stress compared with specimens subjected to other stress improvement processes. In the specimens subjected to USP and SP with an increased area of surface processing, the large crystal grains of alloy182 are considered to be downsized, leading to an increased number of crystal grains in the X-ray irradiation region and a high measurement accuracy of residual stress compared with that of specimens subjected to WJP.

## 3.3 Sustainability of the compressive residual stress inside the specimen

Figure 6 shows the result of the residual stress measurement in the depth of 10–200  $\mu$ m from the surface of SUS316L and NCF600 at 2 mm from the fusion line. The compressive residual stresses were sustained in the specimens after 200 cycles of 0.07% strain application at 593 K and subsequent thermal aging treatment for  $1.66 \times 10^6$  s at 673 K. For the specimens subjected to stress improvement processes other than polishing (i.e., LP, WJP, USP, and SP), the compressive residual stresses were sustained in SUS316L at a depth of 100  $\mu$ m and in NCF600 at a depth of 200  $\mu$ m. For the specimen subjected to polishing, the compressive residual stress was sustained in both SUS316L and NCF600 in the depth of 10  $\mu$ m.

From the above findings, the compressive residual stress is sustained in welded specimens comprising SUS316L, NCF600, and alloy 182 subjected to LP, WJP, USP, SP, and polishing under the conditions of 60 years operating of a nuclear power plant.





Figure 5 Effect of 200 cycles of 0.07% strain at 593 K and subsequent the thermal aging treatment for  $1.66 \times 10^6$  s at 673 K on surface compressive residual stress in alloy182: (a) LP, (b) WJP, (c) USP, (d) SP, and (e) polishing





Figure 6 Effect of 200 cycles of 0.07% strain at 593 K and subsequent thermal aging treatment for  $1.66 \times 10^6$  s at 673 K on compressive residual stress in depth point: (a) LP, (b) WJP, (c) USP, (d) SP, and (e) polishing



# 4. Conclusions

In this study, the sustainability of the compressive residual stresses in welded specimens subjected to stress improvement processes (i.e., LP, WJP, USP, SP, and polishing) to prevent components of a nuclear power plant from SCCs was examined considering 60-year operation of actual reactors. The obtained results are the following:

- 1) The compressive residual stresses were sustained on the surface of welded specimens comprising SUS316L, NCF600, and alloy 182 subjected to stress improvement processes after 200 cycles of 0.07% strain application at 593 K and subsequent the thermal aging treatment for  $1.66 \times 10^6$  s at 673 K.
- 2) For specimens subjected to LP, WJP, USP, and SP, the compressive residual stresses were sustained in SUS316L at a depth of 100  $\mu$ m and in NCF600 at a depth of 200  $\mu$ m after 200 cycles of 0.07% strain application at 593 K and subsequent the thermal aging treatment for  $1.66 \times 10^6$  s at 673 K.
- 3) For welded specimens subjected to polishing, the compressive residual stresses were sustained in both SUS316L and NCF600 at a depth of 10  $\mu$ m after 200 cycles of 0.07% strain application at 593 K and subsequent the thermal aging treatment for  $1.66 \times 10^6$  s at 673 K.

## Acknowledgement

This study is a part of joint research results by ten electric power corporations (The Kansai Electric Power Company, Hokkaido Electric Power Co., Inc., Tohoku Electric Power Co., Inc., Chubu Electric Power Co., Inc., Hokuriku Electric Power Co., Inc., Chugoku Electric Power Co., Inc., Kyushu Electric Power Co., Inc., The Japan Atomic Electric Power Co., Inc. and Electric Power Development Co., Inc.) and three plant manufacturing corporations (Toshiba Corporation, Hitachi-GE Nuclear Energy, Ltd. and Mitsubishi Heavy Industries, Ltd.). Discussion of these persons concerned is thanked heartily.

## References

- M. Obata, T. Kubo, M. Yoda, R. Saeki and T. Ishikawa: "Relaxation Behavior of Compressive Residual Stress Formed by Laser Peening", Proceedings of the 2009 Annual Meeting of the JSME/MMD CD-ROM Collected Papers, pp.343-344 (2009).
- [2] N. Saito, H. Hato, F. Yoshikubo and R. Morinaka: "Evaluation of Durability in Effect of Residual Stress Improvement by WJP", Proceedings of the Society of Materials Science 59<sup>th</sup> Academic Lecture Meeting, pp.307-308 (2010).
- [3] T. Maeguchi, K. Tsutsumi, M. Toyoda, T. Ohta, T. Okabe and T. Sato: "Study on mitigation of stress corrosion cracking by peening", Proceedings of Japan Society of Maintenology 7<sup>th</sup> Academic Lecture Meeting, pp.568-571 (2010).
- [4] S. Nishikawa, S. Nakada, Y. Horii, I. Komura and A. Yamaguchi: "Stress Relaxation Behavior due to Aging of Stainless Steel and Nickel Base Alloy by Shot Peening", Proceedings of Japan Society of Maintenology 4<sup>th</sup> Academic Lecture Meeting, pp.276-279 (2007).
- [5] R. Sumiya, T. Tazawa, C. Narazaki and T. Saito: "Effect of Applied Stress on the Compressive Residual Stress after Laser Peening", Proceedings of the 2009 Annual Meeting of the JSME/MMD CD-ROM Collected Papers, pp.340-342 (2009).
- [6] K. Masaki, Y. Wakabayashi, Y. Ochi, T. Matumura, Y. Sano and T. Kubo: "High Cycle Fatigue Behavior of Laser Peening treated SUS316L", Proceedings of the 2004 Annual Meeting of the JSME/MMD (2004).
- [7] K. Okimura, T. Ohta, T. Konno, M. Narita and M. Toyoda "Reliability of Water Jet Peening as Residual Stress Improvement Method for Alloy 600 PWSCC Mitigation", Proceeding of the 16<sup>th</sup> International Conference on Nuclear Engineering, ICONE16, May11-15, 2008, Orlando, Florida, USA.
- [8] W. Sagawa, F. Yoshikubo, R. Morinaka, A. Kanno, H. Hato and N. Saito: "Application of Water Jet Peening (WJP) technology to BWR Core Support Structures", Mentenology, Vol.7, No.4, pp.69-76 (2009).
- [9] T. Yoshimura, S. Okido, K. Enomoto, R. Morinaka, K. Hirano and K. Kurosawa, E. Hayashi: "Reduction of Residual Stress on Weld of Components in Nuclear Reactor by Water Jet Peening", The Society of



Materials Science 38<sup>th</sup> Investigative commission about X-ray Material Strength, 2001-Nov-30, pp.38-44 (2001).

- [10] T. Tazawa, R. Sumiya, C. Narazaki and T. Saito: "Effect of Applied Stress on the Compressive Residual Stress of Weldment After Laser Peening", Proceedings of the 2010 Annual Meeting of the JSME/MMD CD-ROM Collected Papers, pp.1263-1265 (2010).
- [11] M. Saito, K. Enomoto, K. Kurosawa, R. Morinaka, E. Hayashi, T. Ishikawa and T. Yoshimura: "Development of Water Jet Peening Technique for Reactor Internal Components of Nuclear Power Plant", Journal of Jet Flow Engineering, Vol.20, No.1, pp.4-12 (2003).
- [12] K. Ogawa, S. Nakada, S. Nishikawa, Y. Horii and H. Murakawa: "Influence of Materials Properties and FEM Elements on Welding Residual Stress Analysis", Proceedings of the Welding Structure Symposium 2006, No.2, pp.705-712 (2006).
- [13] The Society of Materials Science, Japan, The Division Committee of X-ray Materials Strength: "X-ray Stress Measurement Method Standard (2002) - Steel version- (JSMS-SD-5-02)" (2002).
- [14] Japan Nuclear Technology Institute: "The Guideline of Preventive Maintenance Processes [Stress Improvement Process by Polishing] ", pp.5 (2009).
- [15] S. Nishikawa: Improvement of stress corrosion cracking resistance in high temperature pressurized pure water and cracks detectability by ultrasonic test in type 600 nickel base alloy weld, a thesis for a doctorate of osaka university (2010).
- [16] H. Hato, K, Ohashi, Y. Matsui, S. Fukaya, N. Saito, K. Kurosawa, J. Kaneda and H. Sakai: "Water Jet Peening", Journal of Japan Laser Processing Society, Vol.17, pp.27-34 (2010).