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Development of Surface Modification Technology for CEDM Nozzle and Fatigue Enhancement of Ni-based Alloy

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Abstract:

Control element drive mechanism (CEDM) nozzle is manufactured as welded on the reactor vessel and currently uses Inconel 690 alloy. The top of the reactor is equipped with about 100 CEDM nozzles with an internal diameter of about 70 mm. Relatively large inlet/outlet nozzles are equipped with two outlet nozzles and four inlet nozzles on the reactor wall. The inner diameter of the nozzle is vulnerable to stress corrosion cracking (SCC) and fatigue. An ultrasonic nanocrystal surface modification (UNSM) treatment is applied to the inner diameter of the nozzle. The ultimate goal is to improve the service life of parts by introducing compressive residual stress and suppressing primary water stress corrosion cracking (PWSCC).
The main purpose is to design and fabricate a UNSM treatment device for the internal diameter processing of CEDM nozzles. In order to develop the UNSM system, the basic technology such as the development of UNSM tooling is developed and the mechanical properties and fatigue performance of Inconel 690 alloy before and after UNSM treatment are evaluated and compared. The inner diameter of the nozzle was treated by a newly developed UNSM treatment device under the optimized treatment parameters. It was found that the mechanical properties and fatigue performance of nozzle were improved in comparison with the untreated nozzle, which may be attributed to the increase in hardness and induced compressive residual stress.
Keywords: *CEDM nozzle, Ni-based alloy, fatigue, UNSM.*

I. INTRODUCTION

Nowadays, Korea generates about 30% of the total electricity through nuclear power generation [1]. The design life of the initial nuclear power plant is about 40 years, and some nuclear power plants have reached the design life or are operating after extended life. Nuclear power plants operating near or beyond the design life have potential risks, and there are ongoing cases of generation disruption due to various causes within the reactor. Currently, newly constructed nuclear power plants are increasing the design life to more than 60 years [2]. Accordingly, various efforts are being made to improve the critical life of core components for operating nuclear power plants. The life of components is also improving, but one of the most frequently encountered problems in nuclear power plants is primary water stress corrosion cracking (PWSCC) and fatigue, which occurs at nozzles and heterogeneous welds within the reactor.

Efforts have been made to improve the material properties in order to curb the occurrence of these PWSCCs and to solve fundamental problems that improve their lifetime [3]-[4]. Inconel materials are now being used in new nuclear power plants. Nuclear power plants are also turning from Inconel 600 alloy to Inconel 690 alloy. However, it is now a problem that the conversion to Inconel 690 alloy alone is not proven to eliminate PWSCC inherently during long periods of operation to extend the design and operating life of nuclear power plants. In order to solve these problems, a number of investigations around the world have been done to solve the tensile

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residual stress in the nozzle and the welded part and to add the compressive residual stress to improve the PWSCC resistance [5]-[6]. Surface engineering can introduce a severe plastic deformation and induce a high compressive residual stress to the inner and heterogeneous welding parts of these nozzles, and basic tooling and system technology for applying them to the nozzle area has not yet been established. Designing a new surface modification technology and development of system technology are urgently needed to prevent the risk of PWSCC present in nozzles and heterogeneous welding parts.

The control element drive mechanism (CEDM) nozzle is manufactured as welded on the reactor vessel as shown in Fig. 1 [7], and currently made of Inconel 690 alloy. The top of the reactor is equipped with about 100 CEDM nozzles with an internal diameter of about 70 mm as shown in Fig. 1 as well. Relatively large inlet/outlet nozzles are equipped with two outlet nozzles and four inlet nozzles on the reactor wall. The inner diameter of the nozzle is vulnerable to stress corrosion cracking (SCC) and fatigue, and in order to solve this problem, an ultrasonic nanocrystal surface modification (UNSM) technology was applied to the inner diameter of the nozzle. The ultimate goal is to improve the service life of parts by the application of severe plastic deformation and compressive residual stress and suppressing PWSCC using a newly developed UNSM technology that allows to treat the inside of the CEDM nozzles. In order to reach the goal a new UNSM device was designed for the internal diameter processing of CEDM nozzles. It is a challenge, but it is very meaningful research and development. The fatigue life and some surface properties of Inconel 690 alloy before and after UNSM treatment were characterized and discussed.

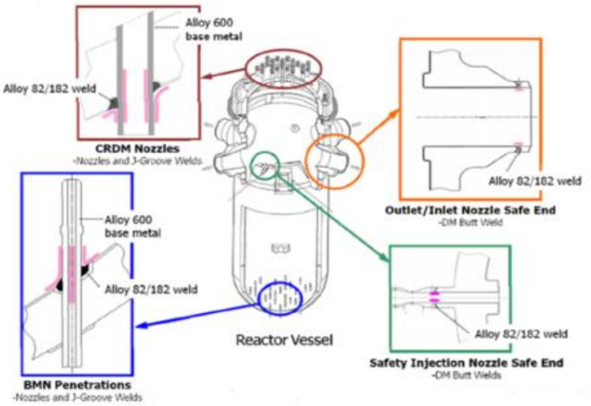

Fig. 1. Types of nozzles used in nuclear reactors.

II. EXPERIMENTAL PROCEDURE

A. Development of UNSM device for CEDM nozzle

The 40 kHz oscillator was designed as shown in Fig. 2 for the development of UNSM device using a 40 kHz frequency domain. In order to directly enter and process an internal diameter of about 70 mm, the length of the 40 kHz oscillator must be less than the internal diameter of the CEDM nozzle. The 40 kHz oscillator length determined in this design is 56.4 mm and the tip length is also 64.4 mm, which is smaller than the CEDM nozzle bore size. The material of the vibrator and the tip was made of titanium alloy Grade 5, and the impact ball was made of cemented carbide (WC).

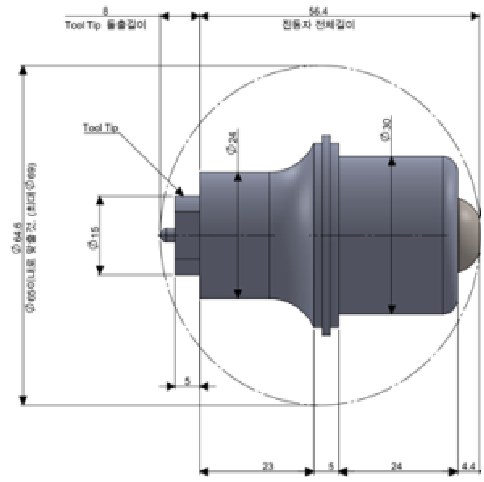

Fig. 2. View of the oscillator with a frequency of 40 kHz.

Fig. 3 shows a newly designed UNSM device with a frequency of 40 kHz for the internal diameter processing of CEDM nozzle. All the components are compactly designed so that the whole device can be inserted into the CEDM nozzle. Since the reactor material is processed, all parts in the device are made of stainless steel. In order to reduce the size as much as possible, the load-loading method that uses a spring from the load-loading method using the existing gravity was developed. The spring constant value was selected as 1.8 kgf/mm and the spring deformation amount was compressed up to 40% of the spring length to realize the maximum load range in the existing type device.

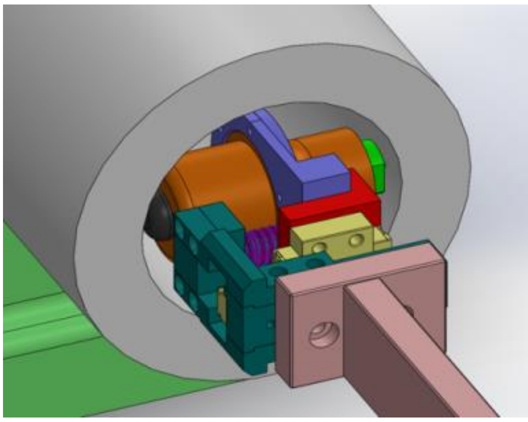

Fig. 3. Schematic view of a newly designed UNSM device with a frequency of 40 kHz for the internal diameter processing of CEDM nozzle.

B. Application of UNSM technology

The processing conditions of the newly developed UNSM device were optimized through the internal diameter apparatus. Table 3 shows the UNSM processing parameters for the CEDM nozzle inner diameter.

Table 1. UNSM processing conditions.

Frequency (kHz)	40
Amplitude (µm)	30
Feed-rate (mm/rev)	0.07
Rotating speed (rpm)	30
Load (N)	54
Ball size (mm)	2.38

C. Specimen preparation and fatigue test conditions

In this study, a commercialized Inconel 690 alloy manufactured by Sandvik was used for the surface properties evaluation and fatigue tests. It is normally used in the annealed condition at 1070 °C followed by air cooling or water quenching with a hardness of about >220 HV. The surface roughness of Inconel 690 alloy before and after UNSM treatment was measured using a two-dimensional surface profilometer Mitutoyo SJ-210, Japan. The surface hardness of Inconel 690 alloy before and after UNSM treatment was measured using a micro-Vickers hardness tester Mitutoyo MVK-E3, Japan. Scanning electron microscope (SEM) and energy dispersive X-Ray spectroscopy (EDS) were used for the surface analysis of Inconel 690 alloy before and after UNSM treatment. X-ray diffractometer was used to measure the residual stress at the top surface and to identify phases in the top surface layer of Inconel 690 alloy before and after UNSM treatment. The fatigue life of Inconel 690 alloy before and after UNSM treatment was evaluated by rotary bending fatigue (RBF) tester at a speed of 3150 rpm with a stress range from 400 to 600 MPa. The length and diameter of the specimens were 100 and 3 mm, respectively.

III. RESULTS AND DISCUSSION

A. Microstructure, Surface Roughness and Hardness

The microstructures of Inconel 690 alloy before and after UNSM treatment are shown in Fig. 4. Surface cracks and scratches were removed through the application of UNSM processing as shown in Fig. 4(b). The comparison in surface roughness of Inconel 690 alloy before and after UNSM treatment is shown in Fig. 5. It was found that the surface roughness was reduced after UNSM treatment from $R_a=0.38\ \mu m$ to $R_a=0.14\ \mu m$, which corresponds to the reduction in surface roughness by more than two times. The comparison in hardness of Inconel 690 alloy before and after UNSM treatment (up to depth of approximately 300 µm from the top surface) is shown in Fig. 6. It was found that the mean Vickers hardness of Inconel 690 alloy was increased from 222 to 360 HV, which is attributed to the grain size refinement following the Hall-Petch relationship [8].

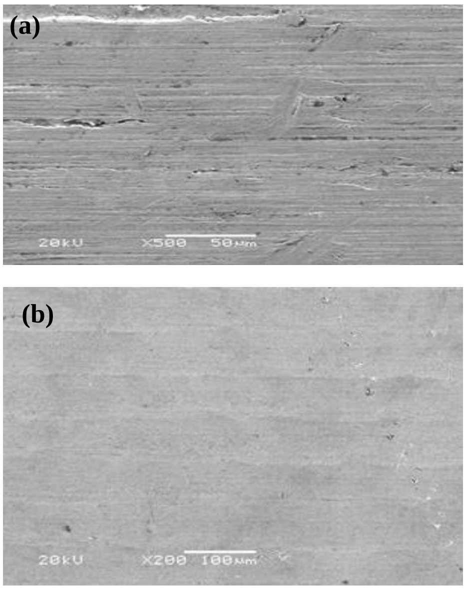

Fig. 4. Comparison in microstructure of Inconel 690 alloy before (a) and after (b) UNSM treatment.

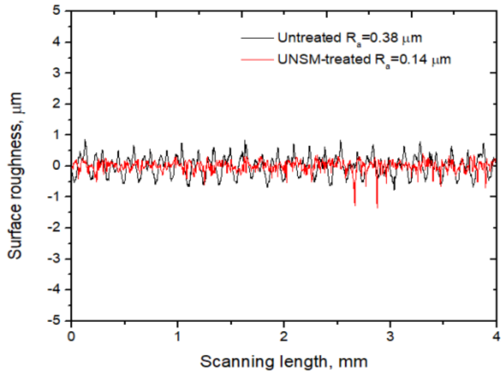

Fig. 5. Comparison in surface roughness of Inconel 6 90 alloy before and after UNSM treatment.

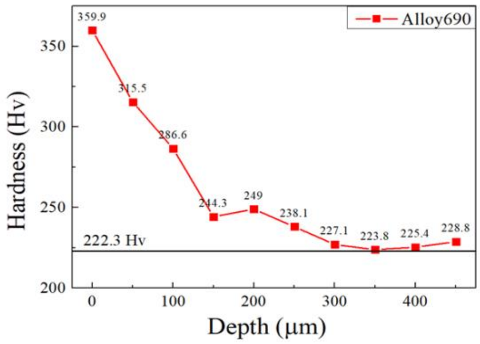

Fig. 6. Comparison in hardness with respect to depth of Inconel 690 alloy before and after UNSM t reatment.

B. XRD and Residual Stress

X-ray diffraction (XRD) patterns of Inconel 690 alloy before and after UNSM treatment are shown in Fig. 7. It was found that the UNSM processing reduced the relative intensity of peaks identifying nanostructured surface and broadened the full-width at half maximum (FWHM). The observed broadening of the peaks after UNSM processing may be attributed to the reduction in grain size and increase in dislocation density [9]. In turn, the grain size refinement is responsible for the higher grain boundary density, while the work hardening is responsible for the higher dislocation density. Residual stress measurements at the surface and a depth of 250 µm and 500 µm from the top surface of Inconel 690 alloy before and after UNSM treatment are shown in Fig. 8. The UNSM processing was able to transfer tensile residual stress into compressive residual stress throughout the depth.

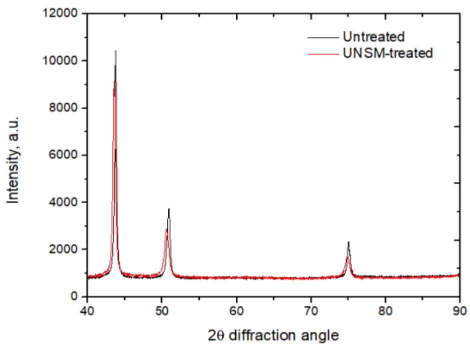

Fig. 7. Comparison in XRD peaks of Inconel 690 all oy before and after UNSM treatment.

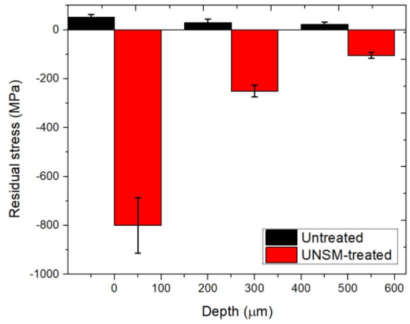

Fig. 8. Comparison in residual stress with respect to depth of Inconel 690 alloy before and after UNSM tr eatment.

C. Fatigue Life (S-N Curve)

The fatigue life (S-N curve) of Inconel 690 alloy before and after UNSM treatment is shown in Fig. 9. The fatigue life of the UNSM-treated Inconel 690 alloy was prolonged compared to that of the untreated Inconel 690 alloy at the same bending stress levels in the range of 400 to 575 MPa. As can be seen from Fig. 9 that the fatigue life of both Inconel 690 alloy before and after UNSM treatment was reduced with increasing the bending stress, which means that the effectiveness of the UNSM treatment diminished with increasing the bending stress. A number of previous studies found that the compressive residual stress introduced by severe plastic deformation is the main property that can improve the fatigue life [10]-[11]. Hence, the transfer of tensile residual stress into compressive residual stress throughout the depth by the application of UNSM treatment plays a dominant role in controlling the fatigue life.

Fractographic observations of the fractured surfaces (at 575 MPa) of Inconel 690 alloy before and after UNSM treatment are shown in Fig. 10. Before the application of UNSM treatment as shown in Fig. 10(a), the cracks in Inconel 690 alloy started from the surface, forming cracks in the center of the specimen. After the application of UNSM treatment as shown in Fig. 10(b), the fatigue failure of Inconel 690 alloy started from the surface and connected to the inside, and plastic deformation was occurred, resulting in small cracks in the center of the fractured area. According to the results, it is suggested that the application of UNSM treatment was beneficial in extending the fatigue life of Inconel 690 alloy in comparison with the untreated Inconel 690 alloy due to the introduction of compressive residual stress and increase in hardness as well.

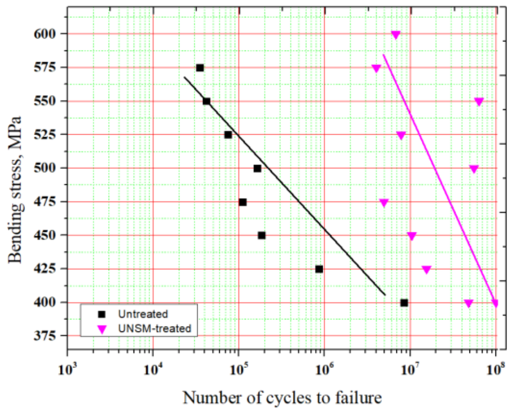

Fig. 9. Comparison in fatigue life (S-N curve) of Inc onel 690 alloy before and after UNSM treatment.

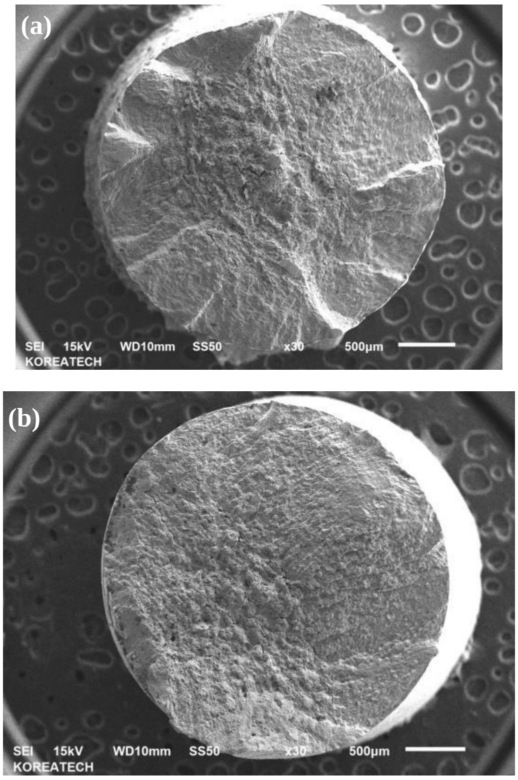

Fig. 10. Fractrography of Inconel 690 alloy before (a) and after (b) UNSM treatment showing the crack initiation site together with a trajectory of fracture, i nner micro-cracks and plastic deformation regions.

IV. CONCLUSIONS

In this study, the fatigue life of Inconel 690 alloy before and after UNSM treatment was investigated. A newly designed UNSM device with a frequency of 40 kHz was used to treat the internal diameter of CEDM nozzle. The results revealed that the fatigue life of the untreated Inconel 690 alloy was extended by UNSM treatment at various stress levels. It is concluded that the application of a newly developed UNSM device was beneficial in extending the fatigue life of Inconel 690 alloy in comparison with the untreated Inconel 690 alloy due to the introduction of compressive residual stress and increase in hardness. Now it is possible to improve the service life of parts by the application of severe plastic deformation and compressive residual stress using a newly developed UNSM device that allows to treat the inside of the CEDM nozzles.

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