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# Effect of residual stress induced by pulsed-laser irradiation on initiation of chloride stress corrosion cracking in stainless steel

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ABSTRACT

The atmospheric corrosion test and residual stress measurement were performed to evaluate the effect of laser irradiation on stress corrosion cracking (SCC) initiation. Second-harmonic Nd:YAG laser pulses (pulse width: 10 ns) were irradiated on a type-304L stainless-steel plate. The specimens were placed in a chamber at 353 K with RH=35% for the corrosion test. When laser energies were 30 and 300 mJ, cracks caused by SCC or pitting were observed on the surface of the specimens. The cracks were classified into two types on the basis of cumulative probability distribution; one of the types is related to the laser irradiation condition. The mean maximum crack depths were about 27 and 52 μm when laser energies were 30 and 300 mJ, respectively. These values were the same as the depth at which the tensile residual stress was induced from the surface of the specimen by laser irradiation. These results suggest that the maximum stress corrosion crack depth was caused by the tensile residual stress induced by laser irradiation, and that the crack stopped propagating when the crack depth was larger than several dozen μm in this test set. When laser pulses of 300 mJ energy were irradiated on the surface of the specimen by shot peening, the tensile stress was induced up to 20 μm from the surface, and the compressive stress was observed at a larger depth. These results show that the laser irradiation is less effective in obtaining tensile residual stress of the specimen compared to when laser pulses are irradiated on the specimen treated by shot peening. The depth of tensile stress obtained by laser irradiation is much shorter than that of compressive stress obtained by shot peening.

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## 1. Introduction

Laser surface melting [1] and laser peening by irradiation are used for the surface fabrication or modification of metal materials. Pulsed-laser irradiation generates plasma and causes a plastic deformation by the impulsive pressure of the plasma. Although heat input by laser irradiation results in the occurrence of tensile residual stress on the surface of a metal in general, the use of coatings prevents the ablation and melting at the surface of the metal [2]. The technology of introducing compressive residual stress by irradiation is called laser peening, and this is used to prevent stress corrosion cracking (SCC). Such a surface treatment effect on the residual stress is observed when spark- or laser-induced breakdown spectroscopy [3] is applied to metal materials because the plasma is produced by spark ignition or laser irradiation [4,5].

The pulsed-laser irradiation effects on a metal are heat input and plastic deformation. When the laser pulse width, e.g., the Q-switch laser pulse width, is shorter than several nanoseconds, the effect of plastic deformation is much larger than that of heat input because the laser-induced plasma can be produced with several milliJoules per pulse. Therefore, it is expected that the material composition does not change and the residual stress and morphology at the surface of the material change slightly when a laser pulse of low energy is irradiated on the metal materials. Peyre et al. reported that such a plastic deformation does not affect the occurrence of pitting [6]. On the other hand, Horikawa et al. reported that the crack propagation rate increased at the tungsten inert gas (TIG)-welded joint [7]. Tani et al. reported that chloride-induced SCC of the austenitic stainless-steel (SS) occurred independently of the tensile residual stress value [8]. They have performed the SCC test on the austenitic SS using loading device and showed that the specimen of type 304L SS was fractured even when the applied stress was below 200 MPa which was less than 0.2% proof stress of type 304L SS. The previous studies indicate that the pulsed-laser irradiation on SS induces the tensile residual stress and results in the SCC initiation.

Although pulsed-laser irradiation effects on the surface of metals were investigated experimentally and theoretically upon laser melting and laser peening, almost all the studies reported the relationship between the laser irradiation condition and the properties of metal (e.g., residual stress, morphology, and hardness).

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The susceptibility of a metal to corrosion was also reported when the effect of plastic deformation was dominant, i.e., the input laser energy was small [6,9]. However, the quantitative relationship between the residual stress and SCC or pitting was unclear.

The loading test results reveal the stress threshold at which SCC of active-pass corrosion type in austenite SS occurs [10]. The report shows that the stress threshold is 0.2% proof stress at the chloride-induced SCC of sensitized SS and is lower than 0.2% proof stress at the chloride-induced SCC of unsensitized SS. Takemoto reported that a crack longer than 0.1 mm propagates itself, but a crack shorter than 0.1 mm does not propagate [11]. Although the loading test was examined under the constant loading condition, the crack propagation will be different when the residual stress is induced by laser irradiation owing to the change in the loading value at the tip of a propagating crack.

In this study, the atmospheric corrosion test were performed using type 304L SS irradiated by a pulsed laser to evaluate quantitatively the feature of SCC occurred by irradiation. In addition, the relationships between the tensile residual stress induced by irradiation and the length of SCC were clarified by the residual stress measurement. The residual stress measurement results of the specimen treated by shot peening are also shown to discuss the laser irradiation effect on the residual stress with or without surface treatment.

## 2. Experimental setup

### 2.1. Materials

Type-304L SS of half-inch thickness was used for the experiment. The surface finish was No. 1. Table 1 shows the chemical composition of the test materials. The shape of the specimen and the position irradiated by the laser are shown in Fig. 1. The specimens of $20 \times 30\ mm^2$ area were cleaned with acetone. Laser irradiation was carried out using second-harmonic Nd:YAG lasers (Hoya Continuum, Powerlite 8010) operating at a repetition rate of 10 Hz. The laser pulses were focused by a convex lens of 250 mm focal length and irradiated perpendicularly to the six points on the surface for each specimen. The diameter of the irradiated laser spot on the specimen was about 0.5 mm.

### 2.2. Stress measurement

The residual stress was measured by the X-ray diffraction method (Bruker, D8 Discover). X-ray radiation source of Cr Kα with the applied voltage of 38 kV and the current of 90 mA was used. The 2D method was used for the residual stress analysis [12]. The X-ray beam diameters were set to 0.3 and 0.5 mm to measure the lateral and depth profiles of residual stress, respectively. The detector position was set at 128°. The angle between the normal to the diffracting lattice planes and the sample surface ($\psi$) and the rotation angle of the sample surface ($\varphi$) were set at ($\psi$, $\varphi$)=(0, 0), (15,0), (15, 45), (15, 90), (15, 135), (15,180), (30, 0), (30, 45), (30, 90), (30, 135), (30,180), (45, 0), (45, 45), (45, 90), (45, 135), (45,180), (60, 0), (60, 45), (60, 90), (60, 135), and (60,180) for each measurement point. An X-ray diffraction device (Rigaku, Auto-MATE) was used to measure the circumferential specimen treated by shot peening. X-ray radiation source of Cr Kα with the applied voltage of 40 kV and the current of 30 mA was used. The $\sin^2\psi$ method was used for the residual stress analysis. The X-ray beam diameter was set to 0.5 mm. $\psi$ were set at 0°, 18.4°, 26.6°, 33.2°, 39.2°, 45.0°, 50.8° for each measurement point. In both devices, the X-ray diffracted from ($\gamma$-Fe 220) plane was measured, and the electrochemical polishing was performed to etch the specimen when the depth profile of residual stress was measured. In order to clarify the dependences of laser energy and the number of laser shots on residual stress at the surface of the specimen, the laser energy and the number of laser shots were set to 30, 150 and 300 mJ, and 1, 10 and 100, respectively.

**Table 1**
Chemical composition of tested material.

| Element | C | Si | Mn | P | S | Ni | Cr | Fe |
|---|---|---|---|---|---|---|---|---|
| wt% | 0.010 | 0.060 | 1.19 | 0.032 | 0.002 | 10.33 | 18.37 | Bal. |

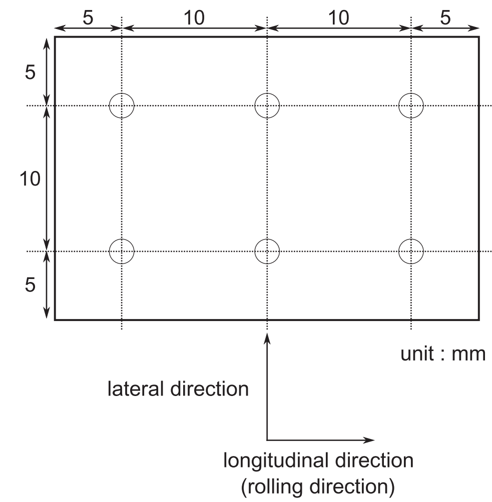


**Fig. 1.** Specimen and point of laser irradiation.

### 2.3. Corrosion test

Droplets (10 μl) of synthetic seawater were placed on the laser-irradiated position of the specimens using a micropipette. The major components of the synthetic seawater are NaCl (2.45 wt%), $MgCl_2$ (1.11 wt%), $Na_2SO_4$ (0.41 wt%), $CaCl_2$ (0.15 wt%) and so forth. The specimens were placed in a chamber with the temperature and relative humidity controlled at 353 K and 35%, respectively. The experimental setup satisfies the environmental condition for the SCC initiation because the SCC initiation was reported using the type 304L SS sprayed with synthetic seawater under the environmental condition (353 K with RH=35%) [8]. The surfaces and cross sections of the specimens were observed after test durations of 1500 and 3000 h. In order to observe the cross section of the specimens, a wire cutting-off machine was used to cut the line passing through the center of the laser-irradiated position. The crack depth was defined as the length from the surface of the specimen to the tip of the crack observed at the cross section of the specimen.

## 3. Results and discussion

### 3.1. Feature of crack depth

Typical images of the cross section and surface of the specimen after the corrosion test are shown in Fig. 2. Microscopic cracks observed around the laser-irradiated position were produced through the No. 1 surface finish. The other cracks were not observed at the laser-irradiated position owing to the surface melting of the specimen. SCC and pitting were observed at the point on which the droplets of synthetic seawater were placed. Results of field investigation of the SCC of austenite SS under the

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