Development of Laser Peening to Prevent Stress Corrosion Cracking of Pressure Water Reactor

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1. Introduction

Preventive maintenance has been received vast attention to enhance the reliability of components and to eliminate the outages in nuclear power plant. Mechanical shot peening technique, which employs the impulsive effect of high-speed metal ball, has been used to retain compressive stress on the surface of nuclear power plant components for many years [1]. Residual compressive stress on the metal surface has been used to extend the fatigue life and to prevent stress corrosion cracking. Similarly, an intense laser irradiation under water can introduce compressive stress on an immersed metal surface by high-pressure confined plasma. Laser based technology is considered to be the best tool for remote processing in nuclear power plants, and especially so for the maintenance of nuclear reactor. Since there is no reactive force against laser irradiation, accessibility can be greatly improved by simple handing system. Further more, minimized heat effect on material extends the applicability to neutron-irradiated materials.

The first laser peening experiments took place more than 30 years ago at the Battelle Institute in Ohio. However, it was only recently (1996)—with the advent of high-power solid-state lasers at higher repetition rates and better beam quality—that this method began to compete with traditional shot-peening methods, which employ small metal or ceramic particles to deliver the impact. While shot peening and other mechanical surface treatment techniques are only capable of producing compressive stress down to depths of a few tenths of a millimeter, depths of compressive residual stress induced by laser peening are typically on the order of a millimeter or more.

In the present work, we describe the shock wave generation and propagation in metal and compare our results with the Fabbro's model [2]. We use commercially available code named Hyades [3], which is one dimensional Lagrangian MHD code and supports material properties. The shock wave pressure was calculated to evaluate the feasibility of stress investment in laser peening processing. Finally, the result of stress investment by Q-switched Nd:YAG 2nd harmonics is shown to demonstrate the effectiveness of the laser peening method.

2. Laser Peening

When a Q-switched laser is focused on the surface of immersed metal, the surface absorbs the laser energy and evaporates instantaneously through the ablative interaction. The evaporated metal is confined in a narrow space because the surrounding water prevents the expansion of metal vapor. This high-density metal vapor is ionized by inverse bremsstrahlung and forms high-density plasma. Subsequent laser absorption in the plasma generates a heat-sustained shock wave. More than GPa shock pressure can be generated by appropriate laser irradiation condition [4, 5].

A shock wave exceeding the yield strength of the metal propagates into metal and losses the energy as it propagates to create a permanent strain of the metal material. After the passage of the shock wave, the permanent strain remains, and surrounding metal material constrains the strained region as a reaction of elastic strain. Thus a compressive stress is formed on the surface of metal.

Fabbro *et al* developed a laser plasma model to predict a plasma pressure as a function of laser energy density. Their semi-empirical model is one-dimensional hydrodynamic one with assumptions of ideal plasma and elastic bodies for target materials. Even though Fabbro's model is widely used one to understand laser-plasma interaction, it requires many empirical parameters to calculate quantitative laser shock pressure. On the other hands, Hyades code contains the fundamental hydrodynamics, energy transport, radiation transport, atomic physics, magnetic fields, and material strength; it is thus able to simulate more complex experimental situations without empirical data.

The main parameters to include in the simulation code were physical and mechanical properties of Al, the incident power density on the target, the laser pulse duration, and the efficiency of interaction as shown in figure 1.

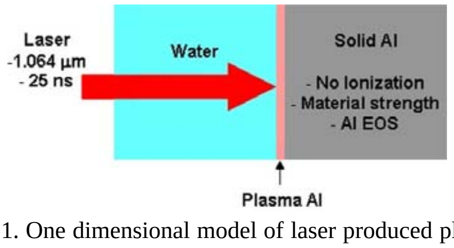

Figure 1. One dimensional model of laser produced plasma.

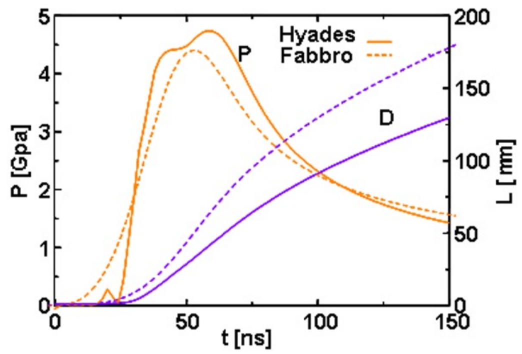

Figure 2. Comparison of Hyades simulation and Fabbro's analytical model.

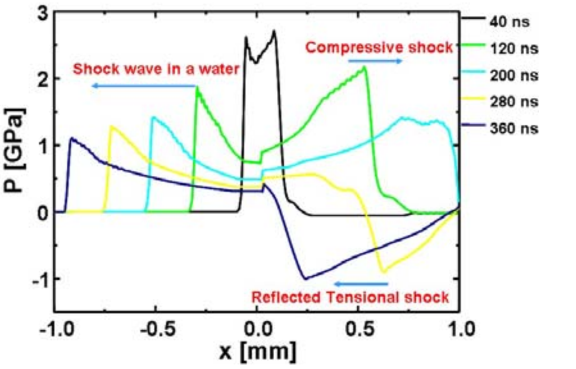

Figure 3. Shock wave propagation in metal and water.

Figure 2 exhibit the typical shock wave evolution on the metal surface and plasma length. The evolution of pressure agrees well. The deviation in the case of plasma length might come from ambiguity in the definition of plasma length in the case HYADES. Figure 3 shows shock wave propagation in the metal and water as a function of time for 25 nsec FWHM laser and 6 GW/cm^2 laser power. As the elastic wave velocity is greater than the plastic wave velocity, elastic precursor break off ahead of shock wave in the metal as shown in Fig. 3.

3. Experiemnt

SUS304 and SUS316 test pieces were immersed in the water and irradiated by Q-switched Nd:YAG 2nd harmonic laser (532 nm, 8 nsec, 200 mJ/pulse) with a focal diameter of 0.8 mm. Schematic diagram of experimental set-up is shown in figure 4. Typically, laser irradiated an area 20x20 mm^2 on the test piece of 50x100 mm^2 with a thickness of 2 mm.

The residual stress was measured by X-ray and neutron diffraction method. Figure 5 shows the in-depth profiles of the residual stress obtained by neutron diffraction method. A residual compressive stress exceeding 100 MPa was developed over 0.5 mm depth in the test coupons. Absolute value of residual stress measured by neutron diffraction was calibrated by X-ray diffraction method.

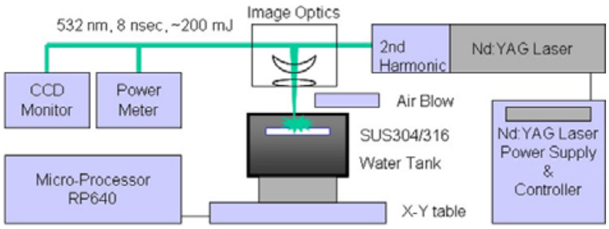

Figure 4. Schematic diagram of the Laser peening system using Q-switched Nd:YAG 2nd harmonic laser

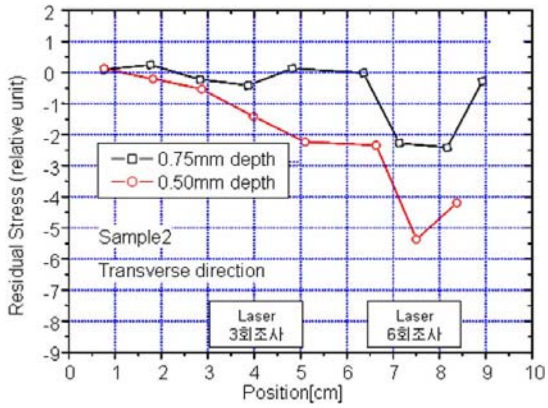

Figure 5. Flow chart of the fringe stabilizer for the Confocal interferometer

4. Conclusion

We calculated shock wave propagation in the metal using HYADES code and compare the results with Fabbro's analytical model. Temporal shock wave profile in the metal and water was also observed. Experimentally, we observed compressive residual stress in SUS304 as a function of depth using X-ray and neutron diffraction method with laser energy 200 mJ, pulse width 8 nsec at 532 nm.

In order to clarify the optimized condition, we are preparing a series of experiments varying the laser pulse energy and spatial profile.

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