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Femtosecond Laser Peening of Friction Stir Welded 7075-T73 Aluminum Alloys

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ABSTRACT

We succeeded in improving the fatigue properties of friction stir welded 7075-T73 aluminum alloy, e.g., prolonging the fatigue life at lower stress amplitude as compared to the base metal, using femtosecond laser peening, which was performed in air without any overlays such as a protective coating and plasma confinement medium, which are necessary for conventional nanosecond laser peening. The results of the plane bending fatigue tests with a stress ratio of $R = -1$ demonstrated that femtosecond laser peening enhanced the fatigue strength of the friction stir welded specimen at 10^6 cycles by approximately 15 MPa compared with that of the base metal, and prolonged the fatigue life of the friction stir welded specimen under cyclic loading at a stress amplitude of 200 MPa by approximately 3.7 times compared with that of the base metal. We suggest that dislocation generation, which occurs behind the shock front under femtosecond-laser-driven shock compression owing to its large shock amplitude, induces surface hardening and compressive residual stresses in a near-surface volume. They prevent the initiation of fatigue cracks on the surface of the specimen, resulting in improved fatigue properties.

1. Introduction

Peening techniques, such as shot peening (Wagner, 2003), ultrasonic peening (Mordyuk and Prokopenko, 2007), cavitation peening (Soyama, 2017) and laser peening (Peyre et al., 1996), introduce plastic deformation in a near-surface volume of a material, which induces work-hardening and compressive residual stress. Work-hardening and compressive residual stress lead to the improvement of fatigue properties, whereas roughened surfaces caused by peening reduce the fatigue properties. Clauer (1996) reported the mechanism of laser peening using nanosecond laser. Laser peening uses a short pulse laser, typically nanosecond laser, to drive a shock wave. When a nanosecond laser pulse is irradiated on the surface of a material or an opaque overlay through a transparent overlay, thin layers of the surface are vaporized into plasma, which is called the ablation phenomenon. The opaque overlay, typically black paint or thin metal film, is treated to protect the material from the heat effects of laser irradiation. The transparent overlay, typically water, confines the expansion of vapor and/or plasma against the surface, resulting in approximately 10 times larger pressure than direct irradiation in air. The steep rise in pressure drives a shock wave that propagates into the material and introduces plastic deformation. Conventional laser peening using a nanosecond laser requires such sacrificial overlays as a protective coating and plasma confinement medium to impart peening effects to a material (Clauer, 1996). Sano et al. (2017) have been developing laser peening using a femtosecond laser, which is called femtosecond laser peening. Femtosecond laser peening can be performed in air without any overlays, which extends the application of laser peening to dry processes or vacuum. Evans et al. (1996) reported that a femtosecond laser pulse drove a strong shock wave above 100 GPa. Cuq-Lelandais et al. (2009) reported that the duration of shock pressure driven by a femtosecond laser pulse was approximately 40 ps. Harzic et al. (2002) reported that the wide of heat affected zone (HAZ) induced by nanosecond laser was 40 μm, whereas that induced by femtosecond laser was less than 2 μm. This indicates that the heat effects of femtosecond laser are negligible owing to its ultrashort pulse width. Therefore, femtosecond laser irradiation in air can introduce plastic deformation, resulting in the introduction of metastable high pressure phases into pure iron (Sano et al., 2003) and silicon (Tsujino et al., 2011). Single shot of a femtosecond laser pulse introduced high density dislocations into silicon (Tsujino et al., 2012) and pure iron (Matsuda et al., 2014a) and induced significant change in dislocation structure in pure iron (Matsuda et al., 2014b). Matsuda et al. (2014c) reported that multiple shots of femtosecond laser pulses changed coarse crystalline iron grains into

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nanocrystals with high density dislocations. Sano et al. (2017) reported that femtosecond laser peening without a sacrificial overlay under atmospheric conditions improved the fatigue properties of 2024 aluminum alloy.

Friction stir welding (FSW), invented at The Welding Institute (TWI) in 1991, is a promising technique for joining aircraft structures made of high-strength aluminum alloys (Dursun and Soutis, 2014). A rotating tool with a shoulder and pin is plunged into a material and translated along a weld line. It generates frictional heats and introduces plastic deformation resulting in circulating flow of the material, which leads to metallurgical joining. FSW generates the following microstructures: stir zone (SZ), thermo-mechanically affected zone (TMAZ) and HAZ. As FSW is a solid-state process, it has many advantages compared with fusion processes, such as fine microstructures, less distortion and residual stress, and the absence of defects originating from solidification (Dursun and Soutis, 2014). Ericsson and Sandstrom (2003) reported that the fatigue properties of friction stir welded aluminum alloy are superior to those of an arc welded alloy. However, the fatigue properties of friction stir welded aluminum alloys are inferior to those of the base metal as demonstrated by Sano et al. (2012) for 6061, Hatamleh (2009) for 2195, and Hatamleh et al. (2010) for 7075. This is due to localized softening originating from the dissolution and coarsening of precipitates and tensile residual stress induced by FSW. The fatigue performance significantly affects the reliability of structures and thus should to be improved.

7075 aluminum alloy, which is a heat-treatable precipitation-hardening aluminum alloy, is widely used in aerospace applications owing to its high specific strength and high fracture toughness. However, it is difficult to weld using conventional fusion processes because it has high sensitivity to hot cracking and the weakened mechanical properties of a weld joint than those of the base metal owing to dendritic structures formed through solidification (Dursun and Soutis, 2014). Although the riveting is now used to join aircraft structures made of high-strength aluminum alloys, it increases the weight of the aircraft and causes stress concentration.

The influences of laser peening on the mechanical properties of friction stir welded aluminum alloys were investigated. Sano et al. (2012) reported that nanosecond laser peening without coating changed residual stresses on the surface of friction stir welded 6061 aluminum alloy from tensile to compressive and improved its fatigue properties. Nanosecond laser peening with coating changed the residual stresses on the surface of friction stir welded aluminum alloys from tensile to compressive and reduced their fatigue crack growth rates as demonstrated by Hatamleh (2009) for 2195 and Hatamleh et al. (2010) for 7075. However, the reduced surface hardness of friction stir welded aluminum alloys was not sufficiently restored by nanosecond laser peening with/without coating as demonstrated by Sano et al. (2012) for 6061 and Hatamleh et al. (2010) for 7075. The surface hardness of friction stir welded precipitation-hardening aluminum alloys strongly depends on the precipitation distribution and slightly on the dislocation (Aydin et al., 2009). Therefore, the effects of work-hardening are smaller than those of precipitation-hardening.

As femtosecond laser peening has negligible heat effects and can induce work-hardening, it has the potential to increase the surface hardness of friction stir welded precipitation-hardening aluminum alloys. This may lead to further improvement of their fatigue properties. However, femtosecond laser peening has never been applied to friction stir welded aluminum alloys and its effects on their mechanical properties are not clarified yet. The purpose of this study is to investigate the effects of femtosecond laser peening without a sacrificial overlay under atmospheric conditions on the fatigue properties of friction stir welded 7075 aluminum alloys. The effects of femtosecond laser irradiation in air on the surface roughness, surface hardness, residual stress, and fatigue properties of base metal 7075 aluminum alloy were investigated first. The peening conditions for friction stir welded 7075 aluminum alloys were selected based on the results of the experiments for the base metal specimen.

Table 1
Chemical composition (wt%) of 7075-T73 aluminum alloy.

Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	V	Zr	Al
0.09	0.28	1.7	2.5	2.5	0.19	5.6	0.03	0.01	0.01	Bal.

Table 2
Mechanical properties of 7075-T73 aluminum alloy.

0.2% proof strength (MPa)	Tensile strength (MPa)	Elongation (%)
419	498	10.5

2. Experimental methods

Specimens of 7075-T73 aluminum alloy with the thickness of 3 mm were used in this study. T73 treatment is an overaged treatment condition to increase the resistance against stress corrosion cracking (SCC). Tables 1 and 2 presents the chemical composition and mechanical properties of the specimen, respectively. FSW was performed in air at room temperature under the following conditions: a rotational speed of 900 rpm, translation speed of 100 mm/min, and load of 5 kN. Fig. 1 shows the cross-section of the FSW specimen with electronic etching using HBF_4 solution with the constant solution temperature of 15℃ and applied voltage of 20 V A polarization microscope was used for observation. The FSW specimen revealed no visible porosities and defects and the grains within SZ were refined.

Fig. 2 shows the schematic illustrations of the experimental procedures. A femtosecond laser pulse (Spitfire; Spectra-Physics, Inc.) with the wavelength of 800 nm and pulse width of 130 fs at full width at half maximum was focused on the mirror-finished surface of the specimen in air using a plano-convex lens with the focal length of 70 mm. The specimen was mounted on an X-Y automatic stage. Before the peening experiments, the ablation depth etched by a femtosecond laser pulse was investigated as a function of the pulse energy to select the peening conditions. The crater depth was measured using a laser microscope and subsequently divided by the number of irradiating pulses to estimate the removed depth per pulse.

In the peening experiments, the X-Y automatic stage successively moved along the X direction at a constant interval and thereafter once moved in the Y direction. This procedure was repeated until the entire specimen surface was peened, as illustrated in Fig. 2(a). The coverage (C_V), expressed as $C_V = \pi D^2/4L^2$ where D is the spot diameter of the laser pulse irradiated and L is the pulse interval, was treated as the number of pulses per area in this experiment. C_V was varied by changing the pulse interval along the X and Y directions. Based on the relationship between the ablation depth and pulse energy, the pulse energies of 0.03, 0.1, and 0.6 mJ, and coverage of 100, 698, and 2768% were selected for the peening conditions.

The surface roughness of the base metal specimen was measured using a laser microscope (VK-9700; KEYENCE) with a wavelength of 408 nm and a depth resolution of 0.05 μm. The surface hardness of the base metal and FSW specimen was investigated using the micro Vickers hardness test (HM-221; Mitutoyo Corporation). It was performed with a load of 1960 mN for the base metal specimen and 980 mN for the FSW specimen and a dwell time of 10 s for both.

The cosα method (μ-X360 Portable X-Ray Residual Stress Analyzer; Pulstec Industrial Co., Ltd.) using Cr Kα radiation with a wavelength of 0.2291 nm was used to investigate the residual stress of the femtosecond laser peened base metal specimen. The X-ray measurement was combined with repeated step-wise electronic polishing to obtain residual stress as a function of the depth from the surface. The diffracted (222) plane of Al was used with the Young's modulus of $E = 71.4$ GPa and Poisson's ratio of $\nu = 0.341$. Further, 10% $HClO_4$ solution was used for electronic polishing at the constant solution temperature of 0℃ and