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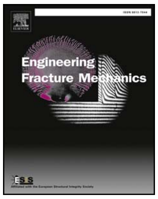

Fatigue strength improvement of an aluminum alloy with a crack-like surface defect using shot peening and cavitation peening

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ABSTRACT

The effects of shot peening (SP) and cavitation peening (CP) on the bending fatigue strength of the 7075 aluminum alloy with a crack-like surface defect were investigated. Test specimens containing a small semicircular slit were subjected to SP and CP. Bending fatigue tests were conducted on the specimens to determine the fatigue strength and critical depth (a_c) of the semicircular slit that can be rendered harmless by peening. The results indicated that fatigue strengths increased by peening and that semicircular slits less than 0.1 and 0.2 mm in depth were rendered harmless by SP and CP, respectively. The a_c values estimated based on fracture mechanics were similar to experimental values, indicating that a_c was affected by the distribution of the compressive residual stress induced by peening.

1. Introduction

The high specific strength of aluminum alloys has extended their potential applications to the aerospace field. Increasing the fatigue strength of aluminum alloys results in longer lifetimes of transportation equipment. Mechanical surface enhancement technologies have been explored by several research groups for improving the fatigue strength of aluminum alloys. Among such technologies, shot peening (SP) is widely applied to increase the fatigue strength of aluminum alloys for aerospace applications. Hammond revealed that SP treatment enhanced the rotating bending fatigue life of the 7075 aluminum alloy due to the presence of compressive residual stress on the surface [1]. Benedetti et al. investigated the beneficial effects of SP treatment on the reverse bending fatigue strength of smooth [2] and notched [3] 7075 aluminum alloy specimens. They indicated that improvement in the fatigue properties after SP treatment was more pronounced for notched specimens [3]. Benedetti et al. investigated the residual stress distribution near shot peened notches using a novel technique based on micro-X-ray diffraction (micro-XRD) measurements [4] and finite element analysis [5]. They suggested that the compressive residual stress was enhanced with increasing sharpness of the notch. Oguri compared the fatigue life enhancement of 7075 aluminum alloy with conventional SP and fine particle shot peening (FPSP) using ceramic particles with a diameter of 50 µm. The results indicated that the fatigue life of FPSP specimens was an order of magnitude longer than those of specimens treated using conventional SP [6]. Inoue et al. showed that the fatigue life of the 7075 aluminum alloy increased after FPSP mainly due to the crack initiation site moving from the surface to the sub-surface due to high compressive residual stress at the surface [7].

Cavitation peening (CP), which does not use shots, has attracted attention as studies have shown that it can improve the fatigue strength. CP is a process that causes plastic deformation of a surface layer of the treated substrate via impact of cavitation bubbles. CP introduces compressive residual stresses without increasing the surface roughness significantly, as it does not involve contact

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between solids. Soyama et al. reported that the rotating bending fatigue strengths of silicon manganese steel [8], aluminum casting alloy [9], and carbonized chrome–molybdenum steel [10] were improved after CP treatment. Fukuda et al. indicated that the fatigue strength of CP specimens of nitrocarburized carbon steel increased by 15% compared with as-machined specimens due to the beneficial effects of the compressive residual stress and increased hardness in the diffusion zone [11]. Recently, Soyama et al. suggested that CP increased the fatigue life of 2017 aluminum alloy plates with a 12-mm-diameter hole due to the introduction of compressive residual stress on the walls of the hole [12].

Most previous studies used smooth specimens and those with a large notch [3] or hole [12] without the presence of small surface defects. In practical applications, small surface defects occur during machining or use and fatigue cracks typically originate on the surface of parts. Thus, small surface defects, such as scratches [7], inclusions [1,7], and pits [13] affect the fatigue strength of aluminum alloys. The reliability of a material increases if small surface defects are rendered harmless using mechanical surface enhancement methods. Increased fatigue strength of materials containing small surface defects has been demonstrated using SP and CP treatments. Takahashi et al. demonstrated that the bending fatigue limits of spring steel containing a semicircular slit increased, and semicircular slits with depths of < 0.2 mm were rendered harmless using SP [14]. Similar effects of SP on the bending fatigue strength were reported for nitride steel [15], spring steels [16,17], medium carbon steels [18,19], and zirconia ceramics [20]. Fukuda et al. investigated the critical depth (a_c) of semicircular surface slits that were rendered harmless after CP treatment for smooth and notched specimens of medium carbon steel. They observed that the a_c values for the notched specimens exceeded those for the smooth specimens due to the higher compressive residual stresses induced in the notched specimens [21]. Existing studies focused only on steels and the effects of SP and CP on the fatigue strength of aluminum alloys containing small surface defects have not yet been reported. Aluminum alloys are more sensitive to surface defects than other metals. Thus, it is important to ensure that surface defects are acceptable level through peening.

The aim of the present study was to investigate the use of SP and CP to improve the fatigue strength of an aluminum alloy containing a crack-like surface defect. In order to achieve this, SP and CP treatments were applied to a high-strength aluminum alloy with a semicircular slit simulating a crack and the fatigue strengths were compared. Furthermore, the critical sizes of surface defects that can be rendered harmless through SP and CP were theoretically and experimentally established.

2. Materials and methods

2.1. Specimen preparation

The test material used in this study was a commercial high-strength aluminum alloy (A7075-T651) which was supplied in the form of a 5 mm rolled plate. Table 1 shows the chemical composition of the test material. The tensile strength of the as-received material was σ_B = 599 MPa and its 0.2% proof stress was $\sigma_{0.2}$ = 549 MPa. Fig. 1(a) shows the bending fatigue test specimen. The surface of the specimen was machined by grinding; as-machined specimens are henceforth referred to as “AM” specimens. The stress concentration factor of the AM specimen was 1.03, meaning that notch fatigue effects were negligible. An artificial semicircular slit, as shown in Fig. 1(b), was introduced perpendicular to the longitudinal direction by electric discharge machining using a tungsten electrode with a thickness of 0.025 mm to simulate an initial crack-like surface defect. The depths of the semicircular slits were a = 0.05, 0.1, 0.2 and 0.3 mm, while the widths of the slits were 0.03 mm. Special attention was paid to producing semicircular slits with an accurate shape. These specimens are henceforth referred to as the “Slit” specimens. SP and CP were conducted on the surface of the AM and Slit specimens.

2.2. Shot peening

In the study, SP was carried out using a direct pressure peening system. The AM and Slit specimens subjected to SP are referred to as “AM + SP” and “Slit + SP” specimens, respectively. Details of the SP conditions used here are listed in Table 2. We used ZrO_2 ceramic shots rather than steel shots in order to prevent undesired galvanic corrosion induced by ferrous contamination. The peening intensity evaluated using an A-type Almen strip was 0.173 mm.

2.3. Cavitation peening

CP was carried out using an atmospheric CP process. The AM and Slit specimens subjected to CP are referred to in this paper as “AM + CP” and “Slit + CP” specimens, respectively. Fig. 2 shows a schematic diagram of the CP nozzle with a bipolar system. High and low-pressure water jets were ejected from the center and surrounding nozzles, respectively. CP was conducted with two passes at a scanning speed of 30 mm/min. Table 3 shows details of the CP conditions used here. The peening intensity evaluated using an N-type Almen strip was 0.06 mm.

Table 1
Chemical composition of test material A7075 (wt.%).

Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Al
0.05	0.22	1.51	0.02	2.69	0.19	5.52	0.04	Bal.