International Journal of Fatigue 106 (2018) 165–174

Contents lists available at ScienceDirect

International Journal of Fatigue

journal homepage: www.elsevier.com/locate/ijfatigue

Influence of prior shot peening variables on the fatigue life of micro arc oxidation coated 6061-T6 Al alloy

L. Rama Krishna*, Y. Madhavi, T. Sahithi, Nitin P. Wasekar, Naveen M. Chavan, D. Srinivasa Rao

International Advanced Research Centre for Powder Metallurgy and New Materials (ARCI), Balapur P.O., Hyderabad 500005, India

ARTICLE INFO

Keywords:
Plasma electrolytic oxidation
Endurance limit
Cyclic load
Residual stress
Anodizing

ABSTRACT

The micro arc oxidation (MAO) coatings of 50 ± 5 μm thickness were deposited on 6061-T6 Al alloy substrates with and without prior shot peening. The peening was carried out using 3-different shot materials namely cast steel, glass beads and alumina having 3-different sizes, each ranging from 212 to 850 μm, at a blast pressure of 1.5 bar and 2.5 bar. The bare, hard anodized, plain MAO and prior shot peened MAO (SP + MAO) coated 6061-T6 Al alloy as a function of (a) maximum alternating stress (5 - different stress levels) (b) shot peening medium (3 - different shot materials) (c) shot sizes (3 - different size ranges for each shot material) were subjected to rotating bending high cycle fatigue tests (R = −1) and the average number of cycles to fail was calculated. The surface residual stresses as well as the residual stress state of the substrate beneath the substrate-coating interface (sub-interface) were analyzed through $\sin^2\psi$ method using conventional and micro X-ray diffraction (XRD) techniques. The results obtained were utilized to understand the effect of surface roughness, surface and sub-interface residual stresses, nature of crack propagation and its deflection on the resulting fatigue life. While both the plain MAO and hard anodized coatings significantly degrades the fatigue life, the prior shot peening followed by MAO coating enhances the fatigue life much better than the bare substrate. On contrary, depending upon the peening parameters employed, the prior shot peening need not guarantee the fatigue life improvement was also noticed. To address this ambiguity, an approach based on integration of shot peening parameters into the "kinetic energy" which is correlated with the "bench mark ratio" (BMR = ratio of fatigue life of coated to the un-coated) as proposed in the present study clearly illustrate the preferred operating window of shot peening parameters resulting in enhanced the fatigue life over 1000–1200% than the corresponding bare substrate.

1. Introduction

Aluminum (Al) alloys have been the interesting engineering materials due to low density, high specific strength and adaptability to diverse manufacturing routes [1]. The precipitation hardenable 6061-T6 Al alloy, with its good weldability and mechanical properties, has been one of the most common Al alloys for general purpose usage including aircraft fittings, landing gear components, hydraulic and brake pistons, bike frames, marine and electrical fittings and others [2–4]. In order to overcome the lower hardness and poor tribological properties of Al alloys, traditionally the hard anodizing (HA), and of late the micro arc oxidation (MAO) also known as plasma electrolytic oxidation (PEO) are the coatings being often resorted to improve both the wear and corrosion resistances [5–8]. However, some of the structural applications as exemplified above need to be additionally protected against the fatigue degradation during their service life [9]. It is well documented in the literature that both the hard anodized and MAO coatings in general degrade the fatigue properties to a considerable extent [10–17]. Furthermore, to worsen the situation, with increasing coating thickness, the rate of fatigue life deterioration gets accelerated while the thinner porous coatings are not adequate to provide the wear and corrosion protection [13,18,19]. Accordingly, over an identical coating thickness window of 10–60 μm, the hard anodizing reduces the fatigue limit by 45–75% while the corresponding MAO coatings reduce the same by 30–60% [18]. The concurrent reduction in fatigue limit is further accelerated under the simultaneous action of corrosion damage [20–23].

Such an inferior fatigue life of these coatings as illustrated above was attributed to the synergistic effect of pores open to the coating surface, porosity present in bulk of the coating and the presence of tensile residual stress around the active fatigue crack-nucleation and crack-propagation regions [24–26]. One of the options available to favorably modify the residual stress state has been to perform shot peening of Al alloy such that the fatigue limit is improved [27–31]. Accordingly, a 25 μm thick MAO coated 2024 Al alloy tested under high cycle fatigue loads at a stress ratio (R) of 0.1 reduce the fatigue life by ~32%, while the substrate surface peened with 280 μm diameter steel

* Corresponding author.
E-mail address: lrama@arci.res.in (L.R. Krishna).

http://dx.doi.org/10.1016/j.ijfatigue.2017.09.020
Received 8 August 2017; Received in revised form 26 September 2017; Accepted 29 September 2017
Available online 05 October 2017

shots prior to the MAO coating deposition enhances the fatigue life by ~85% is reported [32]. However, since the influence of peening parameters such as the shot material and shot size on the fatigue behavior of MAO coated substrates is not well understood, it is not possible to design a comprehensive methodology to enhance the overall fatigue life of Al alloys based on the very limited data reported so far. In addition, the traditional approach of Almen intensity measurement although depends upon the energy of the shot medium that results in plastic deformation of strip as an indicative scale of peening intensity, it often requires separate "stress-free" strips preferably made out of same materials as that of part to be peened [33]. Since the method proposed in the present study involves directly measuring the kinetic energy (velocity) of the shot medium, there is no need to prepare any "stress-free" samples for additional testing.

In view of the above, the present study examines the fatigue life (number of cycles before failure) of bare, hard anodized, plain MAO and prior shot peened MAO (SP + MAO) coated 6061-T6 Al alloy as a function of (a) maximum alternating stress (5 - different stress levels) (b) shot peening medium (3 - different shot materials) (c) shot sizes (3 - different size ranges for each shot material). Further, at each combination of aforementioned parameters, a minimum of 3 samples were subjected to rotating bending high cycle fatigue tests (R = −1) and the average number of cycles to fail was calculated. The shot velocity of each material and size combination just before its impact on the target (6061 alloy substrate) was measured using high speed imaging system (spray watch) and the average kinetic energy of the particle-in-flight has been calculated. The results obtained were systematically analyzed and utilized to propose a comprehensive approach for enhancing the overall fatigue life of MAO coated Al alloy such that the coated samples offer a unique platform for simultaneous protection from fatigue, wear and corrosion.

2. Experimental details

2.1. Substrate materials

In the present study, fatigue samples were fabricated from 6061 T6 Al-alloy having a nominal composition (wt.%) as 0.9%Mg, 0.55%Si, 0.1%Fe, 0.1%Cu, 0.12%Mn, 0.1%Cr, 0.1%Zn, 0.08%Ti and balance Al. Fig. 1 illustrates geometrical details of dog-bone shaped fatigue samples fabricated for conducting the high cycle fatigue tests with and without different pre-treatments. Hard anodized 6061-T6 samples of identical dimensions as shown in Fig. 1 were commercially sourced from M/s Manideep Techno Coats, Hyderabad, India.

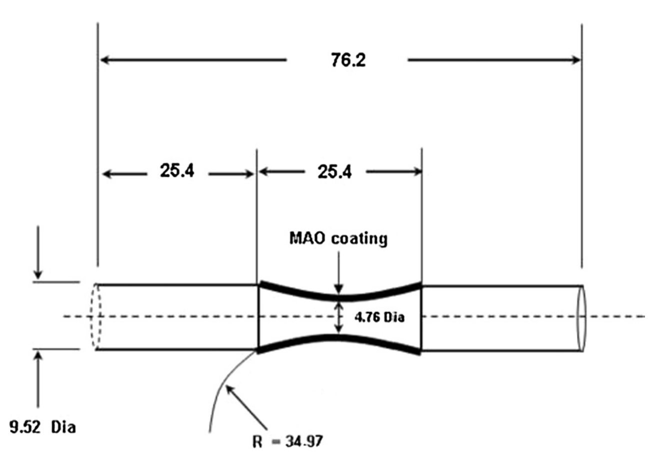

Fig. 1. Geometrical details of fatigue sample fabricated out of 6061 T6 Al-alloy (all dimensions are in mm).

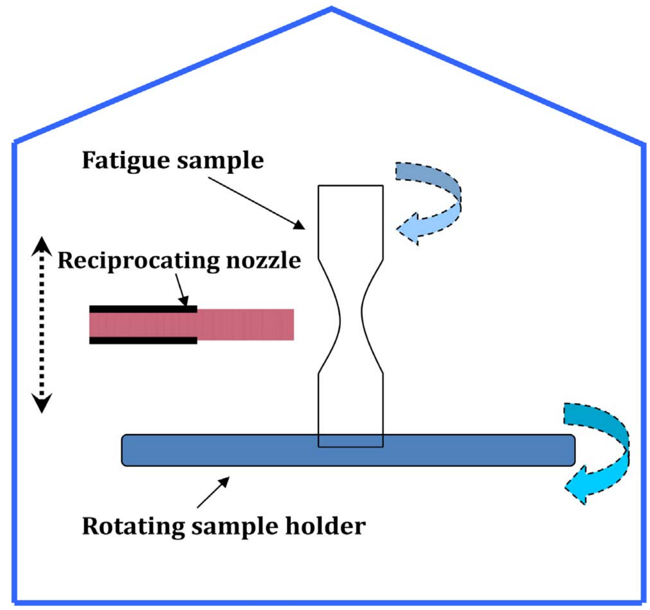

Fig. 2. A schematic of shot peening process with rotating fatigue sample being impacted by the shot plume.

2.2. Shot peening

Shot peening was performed using a specially designed shot peening equipment (PB-606060 SPL, MEC shot blasting equipments Pvt. Ltd., Jodhpur, India). As schematically illustrated in Fig. 2, a tungsten carbide nozzle having 5 mm orifice was positioned at a distance of 5 cm away from the surface to be peened while the nozzle traverses along the longitudinal direction of sample with a cross-head velocity of 22.7×10^{-4} m/s. During shot peening with blast pressures of 1.5 bar and 2.5 bar as employed in the present study, the sample was continuously rotated at 100 rpm. Three different commercially available shot materials each having 3-different sizes such as glass beads (212 µm, 425 µm and 850 µm), alumina (425 µm, 600 µm and 750 µm) and cast steel (425 µm, 600 µm and 750 µm) were utilized for carrying the peening process. The respective shot sizes were termed as fine, medium and coarse under each shot material category. Accordingly, the coarse shots corresponding to glass beads (850 µm), alumina (750 µm) and cast steel (750 µm) were illustrated in Fig. 3 (a-c) respectively.

During shot peening process, the shot velocity was measured using high speed imaging system (Spray Watch 2i, Oseir Ltd., Finland) which employs a diode laser based system (Hi Watch) for illuminating the shots while in-flight [34]. The above system emits three pulses at predetermined time intervals and thereby determines the shot location over two time durations to estimate particle velocity. The velocities of thousands of shots pertaining to different shot materials and size ranges as a function of blast pressure were measured in this manner. The scatter in the measured shot velocities was 8% around the average value of the velocities. Further, the kinetic energy (K.E.) was calculated from the standard equation viz., K.E. = ½ mv^2, where mass of the shot (m) was calculated using its size and density while 'v' is the experimentally obtained average shot velocity.

2.3. MAO coating deposition

The shot peened (SP) and bare (untreated) fatigue samples were subjected to the ultrasonic cleaning in acetone medium prior to the micro arc oxidation (MAO) coating deposition. The shoulder regions of the fatigue samples were masked with insulating tape to selectively achieve the coating in the curved region as shown Fig. 1. The MAO coating unit (75 kVA) designed and built in the author's laboratory was