International Journal of Fatigue 111 (2018) 44–53

Contents lists available at ScienceDirect

International Journal of Fatigue

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

Effect of electrical discharge machining on corrosion and corrosion fatigue behavior of aluminum alloys

Saravanan R. Arunachalam[a], Sarah E. Galyon Dorman[a,*], Richard T. Buckley[a], N. Aidan Conrad[b], Scott A. Fawaz[a]

[a] SAFE Inc, 3290 Hamal Cir, Monument, CO 80132, United States
[b] Department of Engineering Mechanics, United States Air Force Academy, 2354 Fairchild Dr. Suite 2J2, USAF Academy, CO 80840, United States

ARTICLE INFO

Keywords:
Electrical discharge machining
EDM
Corrosion fatigue
Environmentally assisted cracking

ABSTRACT

Electrical discharge machining (EDM) is often used in the manufacturing of fatigue test coupons because it allows for the production of complex shapes and sharp starting notches. However, the effect that the machining process has on the corrosion susceptibility due to the surface alterations is unknown. This work focuses on the effect the machining method has on the corrosion and corrosion fatigue behavior of aluminum alloys. The study is aimed at understanding the influence of EDM processes on environmentally assisted cracking evaluations, namely crack growth rate. Conventional milling and electrical discharge machining were the machining process examined in this study; the machining parameters used were best practices for laboratory fatigue sample production. The following aluminum alloys (AA) 2024-T351, 5083-H116, 6061-T6 and 7075-T651 were evaluated in this study. EDM was performed using a 0.152 mm (0.006 in.) hard brass wire. Surface quality evaluations, microstructural analysis, electrochemical tests and corrosion fatigue testing in sodium chloride (NaCl) solution were completed. The study found corrosion rates are affected by the EDM machining in all aluminum alloys. In final testing, crack growth rate tests were completed in sodium chloride solution with starter notches that were traditionally cut and EDM machined for 7xxx and 2xxx series alloys. The testing showed accelerated fatigue crack growth rates for the samples with EDM notches as compared to cut notches.

1. Introduction

During an outdoor exposure at the Battelle Outdoor Exposure Facility in Daytona Beach, FL, a 5083-H116 aluminum alloy compact tension sample (C(T)) exhibited corrosion damage near the notch, Fig. 1. The notch on the sample had been electrical discharge machined (EDM), while the other sample surfaces had been milled. Based on a visual examination of the sample, it appeared that the 5083-H116 test coupon suffered corrosion damage on the surface adjacent to the EDM notch, while the milled surface was not affected as severely by the environment. The ellipse in Fig. 1 highlights the accelerated corrosion around the EDM notch. Accelerated corrosion around an EDM notch on a laboratory fatigue specimen raises concerns about the impact of manufacturing methods on corrosion performance, and in turn environmentally assisted crack growth testing. Such preferential corrosion damage on a critical location of a test specimen could produce error in damage predictions or material properties based on laboratory testing of specimens.

It is well understood that the surface integrity and the metallurgical state of the surface and subsurface material are greatly influenced by manufacturing processes. Surface integrity (SI) is defined as the inherent or enhanced surface condition of a sample produced during machining or other surface finishing operations [1]. Extensive research has been completed on the SI impacts of machining processes on the mechanical properties and fatigue life prediction of machined products [2,3]. These reviews focus on typical surface alternations that occur during machining such as phase transformations, microhardness and residual stress changes from different manufacturing processes. These surface effects are often correlated to the mechanical performance, primarily fatigue life. Examination of the influence of machining method on a tool steel, SAEJ438b, revealed a 35% loss in fatigue endurance in the case of an EDM machined specimen compared to conventionally milled specimen [4]. While lower residual stresses were observed in the EDM machined specimens compared to milled and ground specimens for steel and γ titanium aluminide (γ - TiAl) alloys; the microstructure alteration and brittle phase formation that occurred during processing appears to have reduced fatigue performance [3]. It is clear from these literature case studies that EDM machining can have

* Corresponding author.
E-mail address: sgd@saf-engineering.com (S.E. Galyon Dorman).

https://doi.org/10.1016/j.ijfatigue.2018.02.005
Received 5 October 2017; Received in revised form 5 January 2018; Accepted 5 February 2018
Available online 07 February 2018
0142-1123/

Nomenclature

ΔK	stress intensity range	N	cycles
a	crack length	NaCl	sodium chloride
C(T)	compact tension sample	OES	optical emission spectroscope
Cu	copper	OCP	open circuit potential
EDM	electrical discharge machining	R	stress ratio
EDS	energy dispersive X-ray spectroscopy	Ra	surface roughness
ESE(T)	eccentrically loaded single edge notch tension sample	Rz	surface roughness
f	frequency	SI	surface integrity
M	molarity	SEM	scanning electron microscope
		wt%	weight percent
		Zn	zinc

a deleterious effect on the fatigue performance when compared to a milling process, particularly in cases of stress-life testing.

Studies on the effect of EDM machining on the mechanical properties in aluminum alloys are limited. EDM machining evaluations in aluminum alloys primarily focus on optimizing the EDM process parameters [4–6]. In the case of aluminum alloy 6061, no microstructural changes or hardness variation were noted when comparing specimens manufactured by EDM to other cutting processes [7]. Another report on 5083 noted that the microstructure and corrosion characteristics of the alloy can be improved by modifying the recast layer chemistry using a silicon electrode in the EDM process [8]. The observation of the preferential corrosion attack near the EDM notch, Fig. 1, and the susceptibility of aluminum alloy 5083 to low temperature sensitized stress corrosion cracking (SCC) due to thermal exposure indicates that there is a strong need for understanding the effect of EDM on a range of aluminum alloys [9]. This data is crucial to determining if EDM is a suitable machining method for the manufacturing of fatigue specimens for testing in accelerated corrosion environments. Any alteration in the microstructure or surface chemistry on the surface or sub-surface of an EDM machined coupon could produce a crack growth rates or corrosion rates that are not representative of the base alloy. To evaluate the effect of EDM an evaluation of the microstructure, corrosion and corrosion fatigue behavior of the following aluminum alloys 2024-T351, 6061-T6, 5083-H116 and 7075-T651was completed using samples manufactured by milling and EDM methods.

2. Experimental procedures

2.1. Materials and machining conditions

The aluminum alloy compositions evaluated are listed in Table 1. Alloy, temper, hardness and conductivity were verified using a Thermo Scientific ARL Quanto Desk - Optical Emission Spectroscope (OES), a Shimadzu micro-hardness tester and a Hockings Autosigma 3000 electrical conductivity meter. All aluminum alloys, 2024-T351, 5083-H116,

Fig. 1. C(T) specimen after two months outdoor exposure at Daytona Beach.

6061-T6 and 7075-T651, tested were from a 6.35 mm (0.25 in.) plate with no clad layer. Rectangular specimens, 5.4 mm × 5.4 mm × 102 mm, were used for characterizing roughness, microstructural changes, hardness and corrosion properties. To compare the manufacturing methods, the parameters used for conventional milling and EDM were the best machining practices for the manufacturing of corrosion fatigue laboratory test specimens. No effort was made to optimize or control machining effects beyond what would typically be done for a fatigue sample. The same machinist manufactured all samples to limit personnel variations. EDM was performed using 0.152 mm (0.006 in.) hard brass wire; the composition was verified to be 40% zinc (Zn) and 60% copper (Cu). The EDM used in this study was an Agie Charmilles FI 240CC which uses deionized water as the machining medium. The EDM machine controls the machining parameters based on user inputs of the sample geometry, substrate (for example: aluminum) and wire materials (hard brass). Machining parameters were not otherwise controlled by the machinist.

2.2. Surface analysis

The surface roughness for all of the milled and EDM aluminum alloy samples was analyzed using a Mitutoyo SJ-400 profilometer. Roughness measurements were performed at four different locations on the machined surface and the average values are reported. Two standard measurements were carried out, an arithmetical mean (average roughness), Ra, and measurement of the difference between the tallest “peak” and the deepest “valley”, Rz. The surface topography of the machined surface was also analyzed using scanning electron microscopy (SEM).

2.3. Microstructural analysis and hardness measurements

Metallographic examinations were carried out on a cross section of the milled and EDM specimens to evaluate the microstructural changes using an optical microscope. The specimens were further examined using SEM to document any alloy chemistry changes that occurred during the machining process with aid of energy dispersive x-ray analysis (EDS). EDS analysis was performed on both the machined surface as well as in the sub-surface of the cross sectioned specimens. The cross sectioned specimens were also used to measure the hardness through the thickness of the sample using a MTS SA2 nano-indenter.

2.4. Corrosion experiments

To evaluate the corrosion behavior of the machined specimens, both quantitative and qualitative tests were performed. Open circuit potential (OCP) and linear polarization resistance were measured using a Gamry Reference 3000 potentiostat. A scan rate of 4 mV/s was used for the polarization resistance testing. A silver/silver chloride (Ag/AgCl) reference electrode was used for tall testing. The OCP was measured for one hour, and the last 30 min were averaged to report an OCP value [10]. The qualitative analysis of corrosion damage was assessed by fully