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Characterization of the surface topography of arc-treated aluminum alloys by fractal geometry

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Abstract

An atmospheric pressure plasma arc discharge creates a complex structure on an aluminum (Al) surface that is a challenging task to characterize by conventional techniques. The solution could be in applying the principles of fractal geometry to characterize the arc-treated aluminum surface while studying profiles obtained by an optical profilometer and SEM (scanning electron microscope) images. The fractal dimension (FD) is determined along with the other conventional surface characteristic parameters (R_a, R_q, S_a, and S_q). The influence of the arc process parameters such as the arc current (I) and plasma torch velocity (v) on the fractal dimension is explored.

Keywords: Arc treated; Fractal analysis; Surface roughness; Aluminum surface

Fractal geometry has shown to be a very useful and effective tool in the topographical characterization of complex surfaces [1]. Topography parameters derived from a fractal model are independent of the resolution of the instrument, while roughness parameters determined by conventional methods are a function of the sampling rate of the specific instrument [2]. Cathodic arcs exhibit many features; e.g., ion current and the motion of cathode spots that can be studied in the framework of fractal theory [3]. The power spectral density (PSD) curve is a way of presenting the data obtained by profilometer and is an effective tool in analyzing surface morphology [4]. The PSD curve is derived from the amplitude of frequency components in the Fourier spectrum and is not influenced by the scan size [5–7]. The spectral method can be used to investigate the fractal properties of a surface [8]. Considering that a surface profile is composed of an infinite series of sinusoids, the power spectral method provides a measure of roughness by representing the square of the amplitude at any frequency associated with that sinusoid [8]. An inverse power law variation of the PSD of a surface with frequency shows an existence of fractal components in the surface topology [2]. The objective of this paper is to characterize the morphological properties of the arc-treated Al surfaces with fractal analysis based on information obtained by the optical profilometer and SEM images.

1. Experimental methods

Coupons were cut from the aluminum 6××× series (Al 6061 and Al 6111) with different thicknesses. However, the result obtained from Al 6061 with a thickness of 6 mm will be presented here. The selected aluminum alloys have very similar chemical compositions and the same expected behavior on the surface. The surface treatment of the coupons was performed by low intensity atmospheric-pressure direct current (DC) arc discharge. A series of experiments were performed on a variety of arc-treated coupons by applying various arcing and scanning parameters according to Table 1. An optical profilometer (Nanovea ST400) was used to obtain 3D and 2D profiles.

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A 400-μm pen was used with a vertical and lateral resolution of 12 nm and 1.3 μm, respectively. The FD was extracted from the 3D and 2D profiles by the *Enclosing Boxes* method named built-in to the Expert 3D, the acquisition software of the profilometer. It should be mentioned that calculating the FD requires significant computational space and time, especially using a fine scan step size.

The SEM images were taken from three random locations on each surface-treated coupon with arcing conditions of $I = 20$, 40, and 60 A and $v = 120$ mm/s, while applying different magnifications of 1, 2.5, 5, 10, and 20 kX. A *Fractal Box Count* tool embedded in the ImageJ Software was used to calculate the FD from SEM images. Application of the *box counting* method to estimate the FD from a binary image is explained by Smith et al. [9].

2. Results and discussion

The typical log–log plot of PSD versus spatial frequency, ω, of arc-treated coupons is depicted in Figure 1 where the PSDs exhibit inverse power law variation. For the most arc-treated aluminum surfaces, there is no ideal straight line for PSD (ω), whereas the graph can be explained by two lines of different slopes. The slope of the straight line in the log–log plot may be related to the FD. However, calculating the FD based on the slope of the log–log plot is one of the major shortcomings of the PSD method where each cycle could have a different slope associated with the dataset of that cycle [10]. Kaye [11] described this situation where the surface possesses a *mixed fractal* behavior and two lines are associated with two *structural* and *textural* regions. Textural and structural regions are associated with the fine scale process controlling the surface roughness and surface at larger scales, respectively [12]. The transition from the textural to structural region might occur due to physical process during the surface generation or, the size of subunits forming the surface structure [12].

Nine coupons were examined for the existence of a correlation between the FD with respect to the arcing process parameters (I and v) and surface roughness parameters (S_a [arithmetical mean height] and S_q [root–mean–square height]). It was observed that the FD decayed by increasing v with a good linear correlation, regardless of I, as presented in Figure 2. This result was confirmed by another series of experiments using Al 6111 with a thickness of 1.2 mm. Generally, it could be said that by increasing v the surface roughness (S_a and S_q) declines; however, this behavior is neither consistent nor predictable.

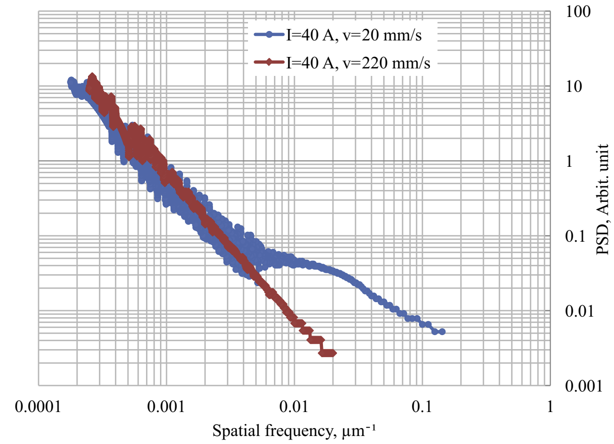

Figure 1. The log–log plots of PSD versus ω of surface-treated coupons with arcs of: $I = 40$ A and $v = 20$ mm/s, $I = 40$ A and $v = 220$ mm/s.

Interestingly, an investigation of the relationship between the FD and surface roughness parameters revealed that the values of FD correlated to S_a with a partial linear or second-order polynomial, regardless of the arcing parameters. A second-order polynomial fits negligibly better than a linear correlation where R^2 is 0.692 and 0.691, respectively (see Figure 3). The regression analysis of FD (S_a) for Al 6111 coupons with a thickness of 1 and 1.2 mm showed that the values of FD correlated to S_a with either a linear or a second-order polynomial fit, depending on the arcing and scanning conditions.

The fractal analysis of SEM images was performed. Figure 4 shows the FD as a function of the image magnification along the typical skeletonized SEM images. It could be said that the FD was increased by increasing I, regardless of the magnifications. The FD was continuously decreased by increasing the image magnification, irrespective of the arcing condition, and reached a plateau except for the case of $I = 40$ A and $v = 120$ mm/s. The treated

Table 1
The conditions of three series of experiments performed on arc-treated parameters.

Experiment conditions		A
Coupon parameters	Al sheet	6061
	Thickness (mm)	6
Arcing parameters	I (A)	20, 40, 60
	v (mm/s)	20, 120, 220
	Surfaces produced	9
Scan parameters	No. of areas for each arcing condition	3
	Area dimension (mm^2)	0.5 × 0.5
	Step size (μm)	0.5
	Data acquisition rate (Hz)	1000