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A review of quantification of lithic use-wear using laser profilometry: a method based on metrology and fractal analysis

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ABSTRACT

Over a decade of experimental lithic use-wear analysis using laser profilometry has led to the development of a method to measure surface modification due to wear in a reliable fashion. This research demonstrates that surface roughness can be documented on experimental stone tools made from a variety of raw material types, including chert, flint, and obsidian, using the laser profilometer, but that determining root mean square roughness (R_q) and a fractal dimension (D_r) may not always be possible. However, when coupled with scale-sensitive fractal analysis, specifically relative length (RL), and the *F*-test (MSR), it is possible to mathematically discriminate both used and unused surfaces on flint flakes, as well as used flake surfaces worn against different contact materials. This research has also identified some potential limitations associated with measuring stone tool surfaces using the profilometer, which affect this method's ability to quantify surface roughness on some experimental stone tools.

1. Introduction

The widespread adoption of microscopic techniques for the purposes of lithic use-wear analysis by numerous archaeologists over the past fifty years stands as a testament to the desire to understand stone tool function for the purposes of reconstructing past behaviors of humans and their hominin ancestors (e.g., Anderson, 1980; Aoyama, 2007; Hurcombe, 1992; Keeley, 1980; Knutsson, 1988; Lemorini et al., 2006; Mansur-Franchomme, 1983; Moss, 1983; Odell, 1981, 1994; Semenov, 1964; Shea, 1993; Stemp et al., 2010b, 2012; Tringham et al., 1974; Vaughan, 1985; Yerkes, 1983). Although there was some early experimentation with methods to document surface wear quantitatively (e.g., Keeley, 1980; Beyries et al., 1988; Dumont, 1982; Grace et al., 1985), the majority of these were not very successful. More recently, greater attention has been placed on the development of methods to quantify lithic use-wear, including image or 'gray-scale' texture analysis (Álvarez et al., 2012; Barceló et al., 2001; Bietti, 1996; Gonzalez-Urquijo and Ibañez-Estevez, 2003; Grace, 1989; Grace et al., 1985; Knutsson, 1988; Lerner, 2007; Rees et al., 1991; Vila and Gallart, 1993) and metrology (Anderson et al., 1998, 2006; Evans and Donahue, 2008; Evans and Macdonald, 2011; Faulks et al., 2011; Kimball et al., 1995, 1998; Stemp and Chung, 2011; Stemp et al., 2008, 2009, 2010a, 2012, 2013; Stemp and Stemp, 2001, 2003; Stevens et al., 2010); some of which are discussed in this special issue. Reasons for looking to methods based on quantification include the use of many individualized qualitative approaches by different analysts (e.g., Kajiwara and Akoshima, 1981; Keeley, 1980; Plisson, 1985) based on a few minimally standardized microscopic methods, difficulties with the comparability of use-wear data between these analysts, lack of agreement concerning the process of wear formation (e.g., Anderson, 1980; Christensen, 1998; Fullagar, 1991; Ollé and Vergès, 2008; Witthoft, 1967), as well as debates over the subjective nature of visual microscopic examination and questions associated with its accuracy (Bamforth, 1988; Bamforth et al., 1990; Evans, in this volume; Grace, 1990; Hurcombe, 1988; Moss, 1987; Newcomer et al., 1986, 1988; Odell and Odell-Vereecken, 1980; Rots et al., 2006; Shea, 1987).

One of the best ways to initially establish the reliability of a method to document use-wear on stone tools from archaeological deposits is through the implementation of a program of experimental replication. This paper discusses the history of the development of a method based on metrology using a surface measurement system – laser profilometry. In these experiments, mathematical algorithms, including root mean square roughness (R_q), fractal dimension (D_r), and relative length (RL), were used to calculate stone tool surface roughness or texture. This research using experimental stone tool replicates and the laser profilometer highlights both the strengths and limitations of this method.

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2. Method

2.1. Measurement system – laser profilometry

A variety of surface measurement systems have been employed by materials scientists to document surface structure and surface wear (e.g., Abdullah et al., 2012; Brown and Savary, 1991; Burke et al., 2000; Creasey et al., 1997; Magonov, 1993; Perry, 1996). For the lithic use-wear experiments discussed in this paper, a laser profilometer manufactured by Ulrich Breitmeier Messtechnic (UBM) was chosen because it is a non-destructive, non-contact system that has been heavily tested to industrial standards in terms of surface measurement (ASME B46.1, 2002; ISO 4287, 1997; see DIN 4776, 1990). To measure a surface, the profilometer uses a semiconductor to produce a laser that is focused to a spot by an objective lens. The spot diameter and sensor stand-off are a function of the lens such that the greater the numerical aperture, the smaller the focused beam diameter and working distance. The light is reflected by the sample being measured and is then directed by a beam splitter to a prism. The light is imaged as a pair of spots on a pre-arranged set of photodiodes. The precise focus distance from the sample yields the equal illumination of both photodiodes. When the distance between the sample and the objective lens changes, the imaged focus point and the illumination of the photodiodes is no longer equal. This results in a focus measurement error that is generated by a differential amplifier. To ensure exact measurements, both the spot diameter and its subsequent light distribution must be kept constant. A control circuit monitors the focus error and moves the objective lens according to changes in the lens/sample distance. The lens movement is provided by a coil and magnet arrangement and is recorded by a light barrier measurement system to yield the change in focal distance to produce a two-dimensional profile over the measured length of a surface (Fig. 1). The specifications of the particular instrument used for measurement in the experiments discussed below include: a linear spot diameter of 1 μm, a tolerable inclination of ±15°, a measurement range of ±500 μm, and a vertical resolution of 10 nm.

2.2. Fractal geometry and measurement of roughness

To study complex forms, Mandelbrot (1977: 4, 1982: 4), influenced by the earlier work of other physicists and mathematicians, developed the concept of fractals or fractal sets. Fractals are essentially a family of irregular, complex shapes that typically occur in nature. They demonstrate a number of important characteristics, including self-similarity and scaling. Self-similarity refers to the ability to break an object down into copies of itself at ever decreasing sizes or scales (Hastings and Sugihara, 1993: 1; Lauwerier, 1991: xii). Scaling, or more specifically scale invariance, refers to the characteristic of the shape or irregularity being mathematically (if not visually) identical at all scales, which is determined by power laws (Mandelbrot, 1982: 1; see Lauwerier, 1991: 87–88).

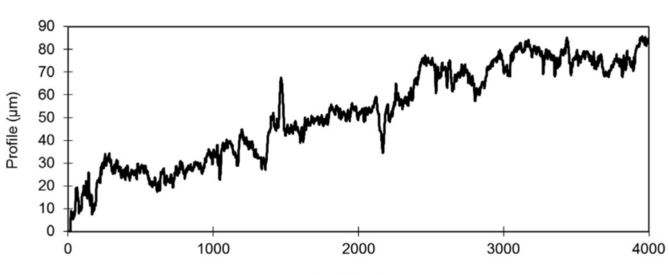

Fig. 1. Example of a surface profile on an unused obsidian flake from the first experiment. The measured surface length is represented along the *x*-axis (4 mm long). The *y*-axis represents the surface elevation (profile) measured along the 4 mm surface length.

Although the concept of incorporating fractal analysis into archaeology is a relatively recent phenomenon (e.g., Zubrow, 1985), the idea took a while to catch on and still does not enjoy widespread use despite its many applications in archaeology (see Brown et al., 2005). Nevertheless, archaeologists have applied the concept of fractals and the use of fractal dimension measurement to understand complex, non-linear relationships in the past (e.g., Kennedy and Lin, 1988; Oleschko et al., 2000; Brown, 2001; Brown and Witschey, 2003; Witschey and Brown, 2003; Brown et al., 2005; Maschner and Bentley, 2003). Due to the characteristics of fractals, they are appropriate to mathematically describe and document the surfaces of stone tools. Because stone tool microtopography necessitates quantitative descriptors well-suited to irregular surfaces, fractal geometry was employed as a means to accurately capture the texture or roughness of the complex surfaces of experimental stone tools (see Mecholsky and Mackin, 1988; Russ, 1994). Relevant to this paper is the reliance by other researchers on multi-scalar or fractal analysis of their surface data to document and discriminate lithic use-wear (e.g., Evans and Donahue, 2008; Evans and Macdonald, 2011; Stevens et al., 2010).

3. The first experiment (1998–2000)

3.1. Experimental methodology

The first experiment involved the use of three flakes made from Onondaga chert and four flakes made from obsidian to test how well the surfaces of different types of stone could be measured using the laser profilometer and whether the surface microstructures would generate mathematical signatures. The tools were used on different contact materials for variable numbers of strokes (Table 1). After use, the tools were cleaned by first washing them with a grit-free detergent and were then sequentially placed in acid solution (15% HCL) and basic solution (15% NaOH) baths. Before scanning, the tools were placed in an ultrasonic tank for a final cleaning. Measurement of the tool surfaces consisted of 4 mm line scans of the used and unused surfaces of the flakes taken parallel to their used edges. A more detailed description of the measurement procedures can be found in Stemp and Stemp (2001). Although the sample size was small, these preliminary tests were primarily designed to see whether future work using a laser profilometer would be productive.

3.1.1. Root mean square roughness (R_q) and fractal dimension (D_r)

Quantification of surface roughness based on the line scans relied on root mean square (R_q) roughness and the fractal dimension (D_r). R_q is commonly used in materials engineering to document surface texture (ISO 4287 1997). However, since this value is length-scale dependent, some calculation of surface measurement that was independent of length-scale was needed.

$$R_q = \sqrt{\frac{1}{N}\sum_{n=1}^{N} z_n^2}$$

To accomplish this, the model of Chauvy et al. (1998), which calculated the fractal dimension (D_r) using the roughness-length method, was employed. This model calculates R_q, over multiple length-scales, using interval lengths (epsilon) that correspond to a small fraction of the overall measured length to calculate the surface roughness based on least square fit. This calculation is repeated as the chosen interval is moved point by point along the measured length. From these data, average roughness and standard deviation values are calculated. This sequence is repeated over increasingly