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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, 2014; 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).

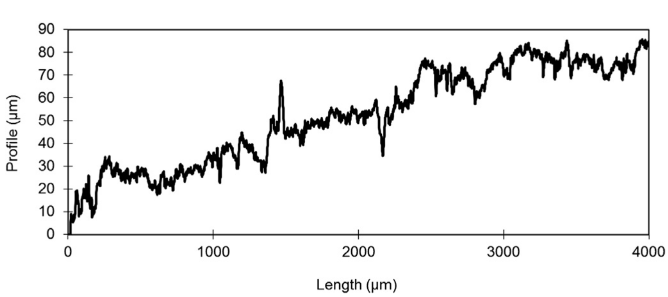

Fig. 1. Example of a surface profile on an unused obsidian flake from the first experiment. The measured surface length is represented along the *x*-axis (4 mm long). The *y*-axis represents the surface elevation (profile) measured along the 4 mm surface length.

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

Table 1
Summary of tool use in the four experiments involving the laser profilometer, including raw material type, number of tools, motion type, contact material type, length of use, line scan length, and number of line scans per tool.

Material	No. tools	Motion	Contact material	Length of use	Line scan length	No. scans (per tool)
First experiment						
Chert	1	Unused	Unused	0	4 mm	4
	1	Saw	Soaked antler	500 reciprocal strokes	4 mm	4
	1	Saw/notch	Pottery	500 reciprocal strokes	4 mm	4
	1	Saw	Shell	500 reciprocal strokes	4 mm	4
Obsidian	1	Unused	Unused	0	4 mm	6
	3	Grind	80 grit SiC paper	2 min	4 mm	3
Second experiment						
Flint	5	Unused	Unused	0	4 mm	3
Flint	3	Saw	Wood	200, 500, 1000, 2000, 3000, 4000, 5000 reciprocal strokes	4 mm	3 per use stage
Flint	3	Saw	Pottery	100, 200, 500, 1000 reciprocal strokes	4 mm	3 per use stage
Third experiment						
Flint	1	Saw	Wood	20 min	2 mm	12 in used region 12 in unused region
Flint	1	Saw	Shell	20 min	2 mm	12 in used region 12 in unused region
Flint	1	Saw	Soaked antler	20 min	2 mm	12 in used region 12 in unused region
Flint	1	Scrape	Dry hide	20 min	2 mm	12 in used region 12 in unused region
Fourth experiment						
Flint	2	Saw	Shell	20 min	2 mm	6 in used region 6 in unused region
Flint	2	Saw	Dry antler	20 min	2 mm	6 in used region 6 in unused region

longer interval lengths to provide roughness values at several length scales plotted in a log–log fashion, as seen in Fig. 2. Using this model, the surface can be mathematically defined as fractal if R_q varies linearly with the length-scale (epsilon). The slope of this line gives the Hürst or roughening exponent H (Brown et al., 1996), which is then used to determine a fractal dimension (D_r) for the surface line, where $D_r = 2 - H$.

3.2. First experiment results

The results of the first experiments demonstrated that laser profilometry could be used to measure the surfaces of stone tools made from chert and obsidian and that R_q and D_r could be calculated for some, but not all, stone tool surfaces. Specifically, D_r could be calculated for the unused chert flake (1.73) and the flake used to saw shell (1.64) thus enabling the mathematical characterization and discrimination of the surfaces on these two tools. The surfaces on the used and unused obsidian tools could also be distinguished from one another based on calculated roughness values at several length scales plotted in a log–log fashion.

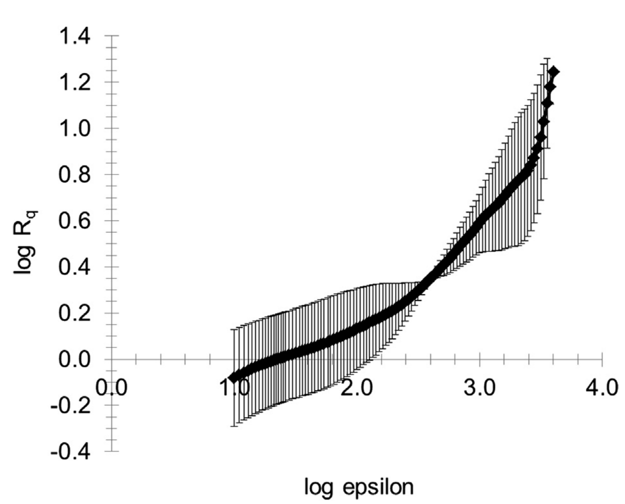

Fig. 2. Example of the mean surface roughness (R_q) on a chert flake used for sawing soaked antler (500 strokes) in the first experiment on a log–log scale.

However, while conducting these experiments, it was noted that surfaces with high inclination angles were difficult to measure because the laser beam was reflected away from the beam splitter and photodiodes. Due to the restriction of the tolerable inclination of the measurement system, only very flat or level flake edges were chosen for measurement. It would be difficult to reliably measure flakes with substantial edge curvature or significantly sloped/undulating surfaces. As well, measurement results varied depending upon the nature of the raw material. The profilometer could measure surfaces of medium/fine-grained chert without difficulty, but the very dark and smooth obsidian flake surfaces could result in the laser no longer reflecting from the surface back to the profilometer (Fig. 3). Although early results were promising, more experimentation was clearly needed.

4. The second experiment (2001–2003)

4.1. Experimental methodology

A second experiment was undertaken that focused on a previously untested raw material, flint, to measure surface roughness using the laser profilometer and calculate R_q and D_r. Based on results of the first experiment, tools made from obsidian were not used and the flakes in this experiment had low inclination angles on their edges and surfaces. This experiment focused on

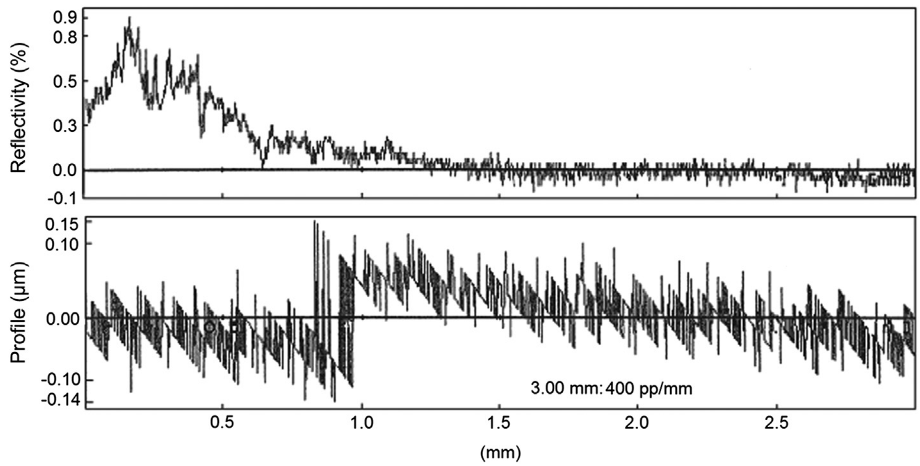

Fig. 3. A laser profilometer line scan showing a zero reflectivity due to the strongly absorbing nature of the obsidian sample (from Stemp and Stemp, 2001: 84, Fig. 3).

the ability to mathematically document the development of wear on stone tool surfaces and the ability to discriminate an unused surface on a tool from a used one. Of secondary interest was the ability to discriminate the surface wear on flakes used on different contact materials. To control for raw material variation, the flakes were all struck from the same East Anglian chalk flint core. Three flakes were used to saw wood and another three were used to saw pottery. Five additional flakes of the same raw material were not used at all so they could serve as a comparative sample to the used ones (Table 1). Each of the flakes was cleaned following the same procedure as in the first experiment (see above) and then scanned using the profilometer after a specific number of strokes. Between each series of strokes, the cleaning procedure was repeated. The wood-sawing flakes were each used for a maximum of 5000 strokes, whereas the pottery-sawing flakes were used for 1000 strokes. The difference in stroke count was based on the more abrasive surface of the sand-tempered pottery, which generated wear at a faster rate. After each stage of use, the tools were cleaned and the newly worn surfaces were scanned in the same locations. The locations were repeatedly found using a datum point etched onto each flake's surface and the profilometer's mapping system. As before, all line scans were taken parallel to the used edge of each flake. Additional details concerning this experiment can be found in Stemp and Stemp (2003).

4.2. Second experiment results

After scanning the flake surfaces, the microtopography data were processed using the same R_q and D_r algorithms as in the previous experiment. The results of these experiments appeared to confirm some of the previous observations and also provided some new information. Discrimination of some used and unused stone tool surfaces was possible and the development of wear based on the increasing number of strokes could be documented on flakes used to saw pottery based on D_r. The increase in D_r was correlated with an increase in the number of strokes [i.e., duration of use] (Table 2). Although surface roughness, based on R_q, could be calculated on the flakes used to saw wood, there was no statistically significant discrimination of used wood-sawing flake surfaces based on R_q and D_r as the number of strokes increased.

Overall, the results of these second experiments were productive and encouraging; however, the inability to discriminate the used surfaces of the wood-sawing flakes as the number of strokes increased necessitated review of the methods employed and an assessment of the overall approach. Failure to significantly discriminate the wood-sawing tools' surfaces as amount of use increased was thought to be attributable to two possible causes – 1) insufficient development of surface wear and the initial line scans using the profilometer or 2) the R_q and D_r algorithms. Following the re-examination of SEM images of the wood-sawing tools after increasing numbers of strokes, it was noted that wear was slow to form in the early stages of use and that wear features were spatially dispersed in the used regions of the flakes' surfaces. Consequently, there were significant regions of natural flint surface that would have been measured by the profilometer's two-dimensional line scans taken in the used regions of the flakes. To test whether the original line scans were, in fact, responsible for the inability to discriminate the different stages of wear development on the wood-sawing tools, the line scan data for all eleven flakes in this experiment were analyzed using two other surface roughness parameters – skewness (R_{sk}) and kurtosis (R_{ku}).

Skewness, as a measure of the peak-height distribution (a.k.a., the amplitude density function), includes the number of heights within the profile versus the profile height with respect to the mean line (ISO 4287, 1997). A negative skew indicates a predominance of plateaus and steep valleys, while positive skew is seen on surfaces with steep peaks.

$$R_{sk} = \frac{1}{NR_q^3}\sum_{j=1}^{N} z_i^3$$

Kurtosis, as a roughness parameter that describes the shape of the peak height distribution, is a measure of the distribution of spikes above and below the mean line (ISO 4287, 1997). For spiky surfaces R_{ku} is greater than 3; for bumpy surfaces R_{ku} is less than 3; perfectly random surfaces have a kurtosis value of 3.

Table 2
Variation of the fractal dimension (D_r) with increasing number of strokes with sawing pottery in the second experiment.

No. of strokes	Unused	100 Strokes	200 Strokes	500 Strokes	1000 Strokes
D_r	1.415	1.507	1.468	1.584	1.663

$$R_{ku} = \frac{1}{NR_q^4}\sum_{j=1}^{N} z_i^4$$

For the surfaces on the unused flint flakes, the skewness value at all length scales was ~0, indicating a random surface with a Gaussian distribution, and the kurtosis value was <3, indicating a bumpy surface, which would be expected for an unmodified fine-grained stone tool surface. The results for measurement of skewness and kurtosis on flint flakes used for sawing wood revealed little change in the calculated values with use, at least within the range of error. For the pottery-sawing flint flakes, the results for measurement of skewness and kurtosis indicated that there was a significant change in the measured values with use (Figs. 4 and 5). Specifically, there was an initial increase in both kurtosis and skewness with number of strokes (up to 500) followed by a decrease (at 1000 strokes). Further, there was an increase in both skewness and kurtosis with an increase in measurement length up to ~2000 μm followed by a plateau. The implementation of skewness and kurtosis to measure the surfaces of the flint tools essentially confirmed earlier results based on R_q and D_r; neither parameter documented significant microstructural change in the wood-sawing tools' surfaces as the number of strokes increased, but did in the case of the tools used to saw pottery. These results led to the conclusion that the comparatively slower rate of wear accrual, the dispersion of the worn surfaces in the 'used' regions of the tools, and the placement of the 2-dimensional line scans resulted in the inability to document microtopographic changes on the used surfaces on the wood-sawing flakes as the number of strokes increased, and that R_q and D_r algorithms were not responsible for the failure to significantly discriminate the surfaces on these flakes with increasing use.

5. The third experiment (2005–2008)

5.1. Experimental methodology

The early experimentation from 1998 to 2003 led to the realization that fractal analysis could be a useful approach to mathematically document and discriminate surface wear on experimentally used stone tools. However, this early work was primarily exploratory in nature and left a number of questions concerning its potential to quantitatively document use-wear unanswered. In 2005, a new experiment in quantification of lithic use-wear using a laser profilometer was undertaken.

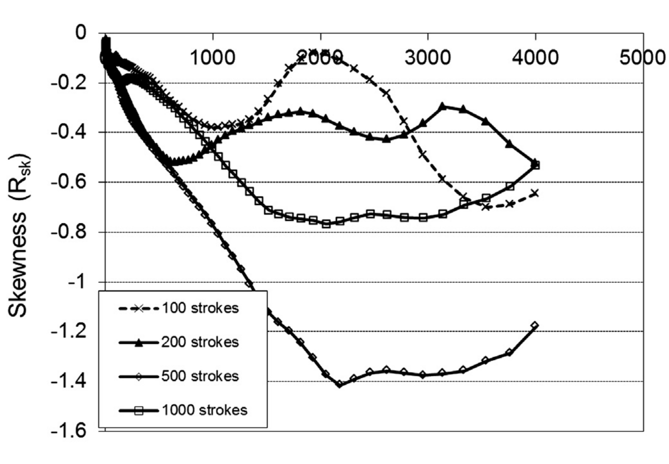

Fig. 4. Skewness (R_{sk}) documented with increasing number of strokes on the flint flakes used to saw pottery in the second experiment.

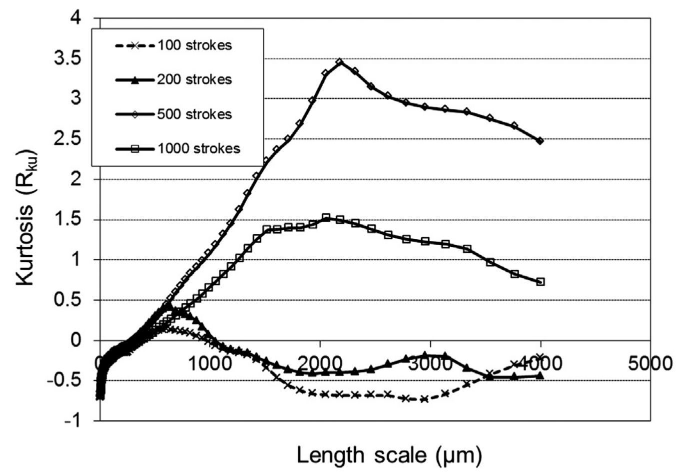

Fig. 5. Kurtosis (R_{ku}) documented with increasing number of strokes on the flint flakes used to saw pottery in the second experiment.

Four East Anglian chalk flint flakes were used on four different contact materials (dry hide, shell, soaked antler, and wood) in the third experiment (Table 1). After 20 min of use, the flakes were cleaned by rinsing them, washing them in a grit-free detergent, and then soaking them in a 15% HCl solution for 15 min. After cleaning, the tools' surfaces were examined using a metallographic microscope [Unitron MS-2BD] at 200× magnification under incident light to ensure all surface debris and any residual materials from the contact materials had been removed. Line scans that measured 2 mm in length were taken parallel to the used edges in both the used (near) and unused (far) regions of each of the four flakes. For mathematical comparisons of surface roughness, the 12 line scans closest to the tool edge in the used region and the 12 line scans furthest from the used edge in the unused region of each tool were employed, although the total number of line scans taken on each flake exceeded this number. This was done to determine whether discrimination of used versus unused surfaces was possible, as in previous experiments, and to establish the scales at which such discriminations might occur. The surface roughness of the four flakes used to work the four different contact materials was also calculated, based on relative length (RL), to test whether the flakes could be discriminated and, if so, to determine the scales at which discrimination occurred.

5.1.1. Relative length (RL)

Because in the first experiment R_q and D_r could not calculate a roughness value for all surfaces measured, relative length (RL) was adopted as the measure of surface roughness for this experiment based primarily on the work of Chris Brown at Worcester Polytechnic Institute (e.g., Brown et al., 1996). As a standardized algorithm based on scale-sensitive fractal analysis, relative length (RL) is calculated as a scale-dependent characterization parameter that relies on the order and spacing of a surface's microtopographical features; whereas, root mean square (R_q) roughness, as a calculated average of surface texture based on profile ordinates, does not. The relative length is the ratio of the calculated length (CL) of the profile divided by the nominal length (NL) (ASME B46.1 2002).

$$\mathrm{RL}(s) = \frac{\mathrm{CL}(s)}{\mathrm{NL}(s)}$$

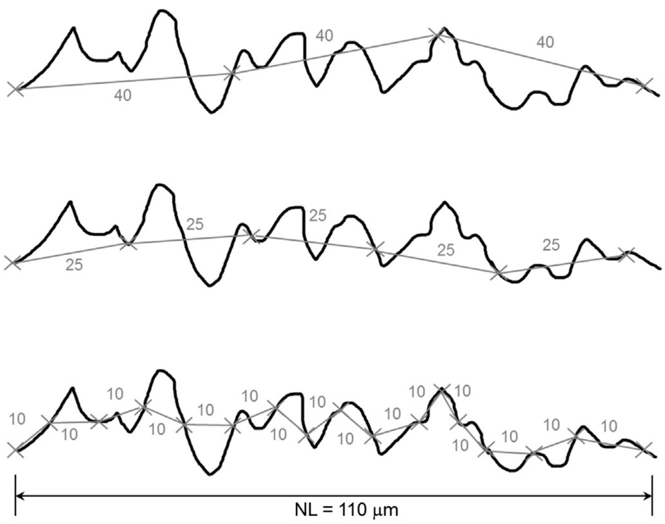

Fig. 6. Length-scale analysis shown on three identical simulated profiles. The profiles have 3 (top), 5 (middle) and 16 (bottom) steps of 40, 25 and 10 μm, giving calculated lengths (CLs) of 120, 125 and 160 μm over a nominal length (NL) of 110 μm, and relative lengths (RLs) of 1.091, 1.138, and 1.455.

This algorithm quantifies the change in apparent, or calculated, length with respect to the scales of observation, or calculation, by a series of virtual line segments (Fig. 6).

Relative length is related to the inclinations of the profile as a weighted average of the inverse of the cosine the line segment makes with the nominal horizontal, or datum (ASME B46.1, 2002; Brown et al., 1996) (Fig. 7).

$$\mathrm{RL}(s) = \sum_{i=1}^{N} \frac{1}{\cos\theta_i}\frac{p_i}{P}$$

For this algorithm, the slope of the log–log plot of relative length versus scale is a measure of the complexity of the surface, with greater negative slopes corresponding to greater complexities. One minus the slope of the length-scale plot is the fractal dimension (ASME, 2002).

5.1.2. The F-test: mean square ratio (MSR)

Surface characterization parameters, such as RL, can be compared statistically at each scale using the *F*-test (Lipson and Seth, 1973), specifically mean square ratio (MSR), to establish a level of confidence for the discrimination of two flake surfaces or two regions on a single flake surface. The *F*-test is used to determine whether the standard deviations from the two measured surfaces can be differentiated by serving as a measure of variance in a multi-factor experiment like this one. The variance demonstrated by the set of observations, in this case the RLs of the two surfaces, will be the sum of the variances of each of the independent sources. The *F*-test compares the variation within each sample to the variations between the samples to test the significance of each of the variations. The MSR of measured data is used to determine whether the observed variation is statistically significant and to what level of confidence. The flint flake surfaces could be discriminated using RL at scales where there was a high level of confidence (above 99%), as indicated by the *F*-test (MSR). Specific descriptions of the procedures used in these experiments can be found in Stemp et al. (2009).

5.2. Third experiment results

The results of this experiment demonstrated that the RLs for all measurements in both the used and unused regions of the four flakes generally increased as the scale of calculation decreased. This is demonstrated by the graph of the RLs from profiles taken in the near (used) regions of the wood-sawing and soaked antler-sawing flakes in Fig. 8. This graph also demonstrates the scale at which discrimination of differently worn surfaces was possible. In this particular case, significant discrimination occurred around 10^{-2} mm. Similarly, the used surface on each of the four flakes that was used on a different contact material could be discriminated from all others at different scales between 10^{-1} and 10^{-3} mm. The surfaces in the unused regions on each of the four flakes could also be discriminated from one another based on the RLs, but at different, and coarser, length scales than the used surfaces.

Based on the MSRs of the RLs of the four flint flakes, all used and unused regions could be discriminated at some scale above the 99% confidence level. The MSRs suggest that the wear that developed during use influences the surface microstructure of the flakes at both the coarser and finer scales. However, it influenced the finer scales, below about 10^{-1} mm, in a way that is characteristic of the contact material because the MSRs at the fine scales for the used regions are relatively large (Table 3). The unused regions could be discriminated at the coarser scales; however, the MSRs at these scales were relatively small (Table 4). As such, it appears that the surface texture or roughness in the used regions, where MSRs are greater, was the result of contact with different materials, whereas surface roughness in the unused regions, where MSRs are smaller, was characteristic of the natural, unmodified fracture surfaces of flint. Based on these results, the wear

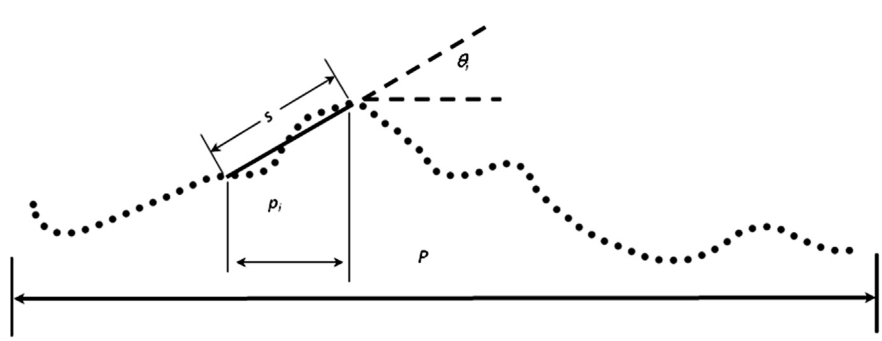

Fig. 7. An illustration of the relation between relative length (RL), calculated from a surface profile, and the inclinations on the surface.

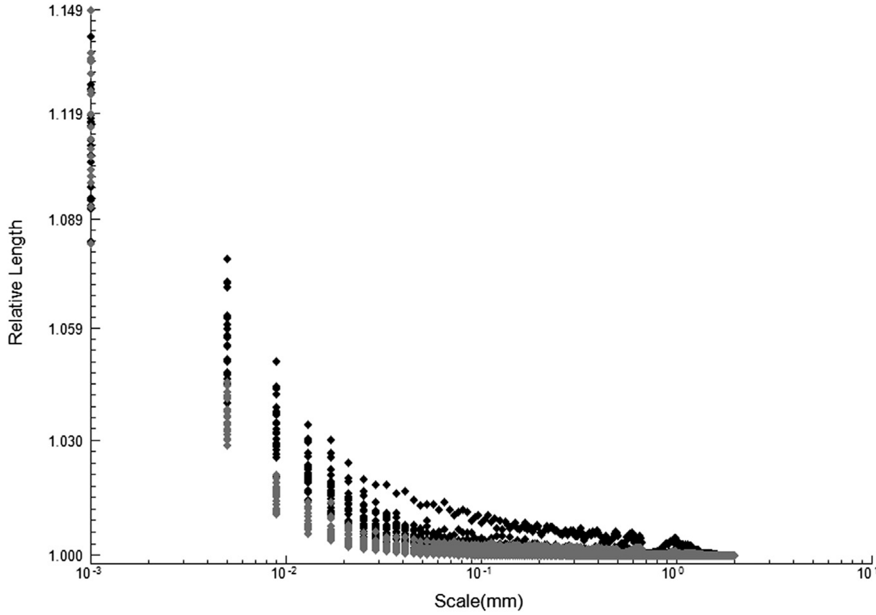

Fig. 8. The relative lengths (RLs) versus scale for the 12 profiles in the near regions for the flint flakes used on wood (◆) and soaked antler (◆) in the third experiment. Significant discrimination occurs around 10^{-2} mm.

mechanisms documented after tool use are such that large features on the stone surface, which are the product of original fracture, are modified tending towards similar textures regardless of the contact material, while the smaller scale features are the result of modification in a manner that is more characteristic of the contact material.

This proposition assumes that the texture of the tool surfaces was the same in the used (near) and unused (far) regions before use, and that the differences in the texture observed in the two different regions of a tool after use are due to the use-wear that developed. Support for this assumption has been provided by two recent experiments to document the unused surfaces of a flint flake and an obsidian blade using a laser scanning confocal microscope (LSCM) equipped with a 20× objective (Andruskiewicz et al., 2012a,b). Six area scans, each measuring 643 × 643 μm^2, taken in the unused region near a tool's edge prior to use were compared to six area scans from the unused region further away in the center of the same tool. Relative areas (RelAs) were calculated for all 12 scanned regions on the flint flake and those on the obsidian blade (ASME B46.1, 2002). For the flint flake, the surface roughness in the two unused regions could not be discriminated above the 95% confidence level at any scale based on MSRs of relative areas (RelAs) (Fig. 9). For the obsidian blade, discrimination of the two unused surfaces was only possible at very coarse scales based on MSRs of relative areas (RelAs), specifically around 10^3 and then around 10^5 μm^2.

6. The fourth experiment (2009–2010)

6.1. Experimental methodology

Based on the results of the third experiment, surface measurements were taken on four more East Anglian chalk flint flakes (Table 1). Each flake was used to saw one of two possible contact materials (dry antler, shell) for 20 min. The methodology and cleaning procedure for this experiment was essentially the same as that for the previous one. However, in this experiment, only 6 line scans (2 mm in length) were taken in both the used and unused regions of each of the four flakes to calculate RLs.

6.2. The fourth experiment results

The results of this experiment provided additional support for the use of laser profilometry and RL to quantitatively document and discriminate stone tool surface roughness. As in the third experiment, RLs generally increased as the scale of calculation decreased and discrimination of each tool's used and unused regions was possible at some scale. Moreover, the used regions on the flakes used on different contact materials could be discriminated based on RLs at fine scales beginning around 10^{-1} mm. For example, significant discrimination based on RLs of the used regions of the two flint flakes used to saw shell and the two flakes used to saw dry

Table 3
Scales for discrimination by relative length (RL) of wear based on the used (near) regions of four flint flakes. All met the minimum confidence level 99% over the scales indicated. Scales in mm.

Contact material	Shell	Wood	Soaked antler
Wood	≤0.93	–	–
Soaked antler	<1.70	0.005–0.93	–
Dry hide	<1.70	<0.017, 0.077–0.57	<0.89

Table 4
Scales for differentiation by relative length (RL) of wear based on the unused (far) regions of the four flint flakes. All met the minimum confidence level 99% over the scales indicated. Scales in mm.

Contact material	Shell	Wood	Soaked antler
Wood	>0.005	–	–
Soaked antler	>0.005	0.005–0.021	–
Dry hide	>0.01	<0.013, 0.025–0.033, 0.045, 0.069, 0.081	0.001–0.04, 0.05, 0.089, 1.11, 1.13 …

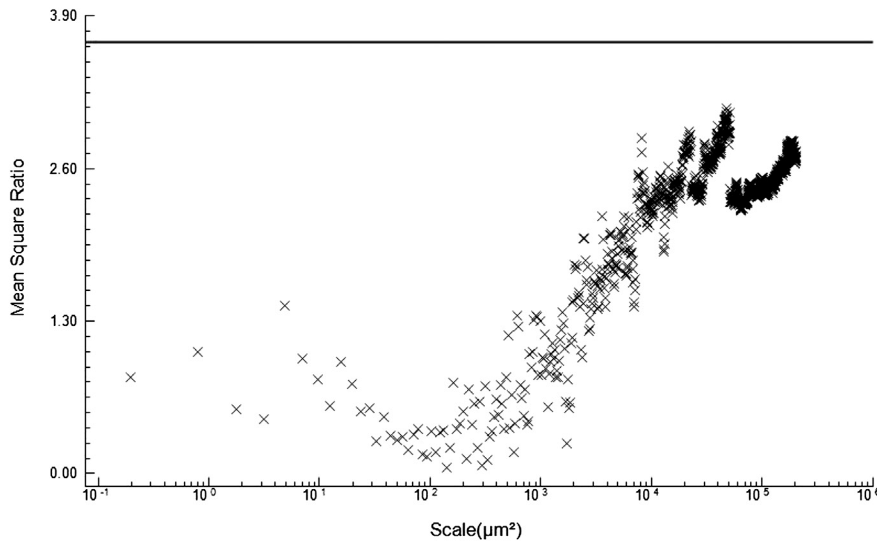

Fig. 9. *F*-test results (MSRs) of the mean relative areas (RelAs) versus scale for the six area scans in the unused region near the flint flake edge versus the six area scans in the unused area in the center of the same flake (×). The horizontal line indicates 95% confidence level for discrimination.

antler occurred at very fine scales (10^{-3} mm) (Fig. 10). Discrimination of surfaces in the unused regions of the four flakes was also possible, but this occurred for RLs at different scales than those calculated for the used surfaces.

Based on the *F*-tests (MSRs), the flakes used on the two different contact materials could be discriminated above the 99% confidence level, primarily over fine scale ranges for the used regions. The used regions of the two shell-sawing flakes could be discriminated from those of the two antler-sawing flakes at the finer scale ranges beginning below 10^{-1} to 10^{-3} mm, as well as at coarser scales around 10^{0} mm at just under 18.0 MSR. However, the unused regions of the two shell-sawing flakes could be not discriminated from those of the two antler-sawing flakes above the 99% confidence level at the finer scales between 10^{-1} and 10^{-2} mm. Discrimination of the unused regions of the shell-sawing and antler-sawing flakes was possible at 10^{-3} mm with a high MSR (Fig. 11) and around 10^{0} mm with very low MSR. Importantly, the MSRs for the discriminations of used regions and the discriminations of unused regions were not the same at the same scales, specifically 10^{-3} mm and 10^{0} mm. Overall, the results of this experiment tend to confirm those of the third experiment in terms of the ability to discriminate the used and unused regions of the flint flake surfaces at various scales, as well as the discrimination at fine scales of the used regions of flakes based on contact with different materials.

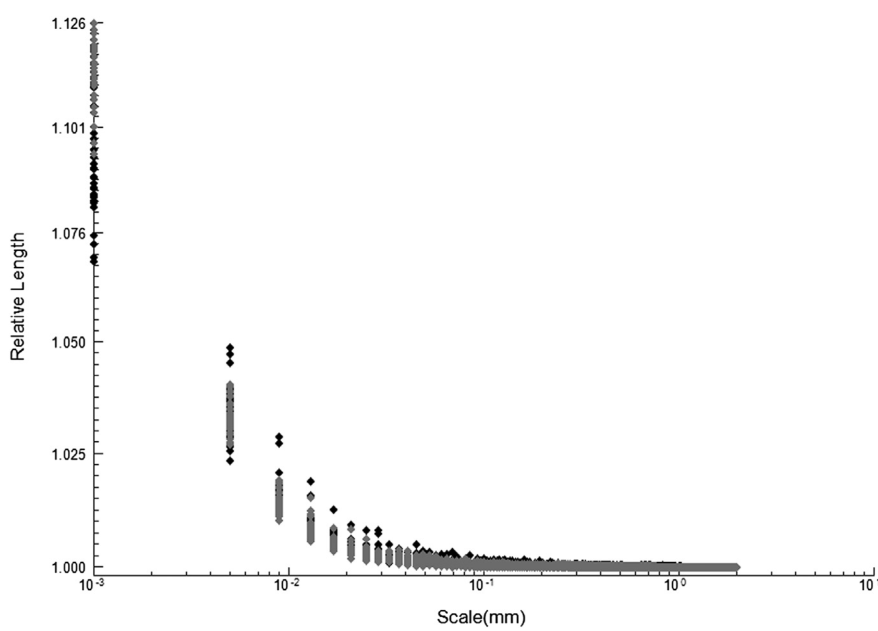

Fig. 10. The relative lengths (RLs) versus scale for the 12 profiles in the near regions of the two flint flakes used on shell (◆) and the two flint flakes used on dry antler (◆) in the fourth experiment. Significant discrimination occurs around 10^{-3} mm.

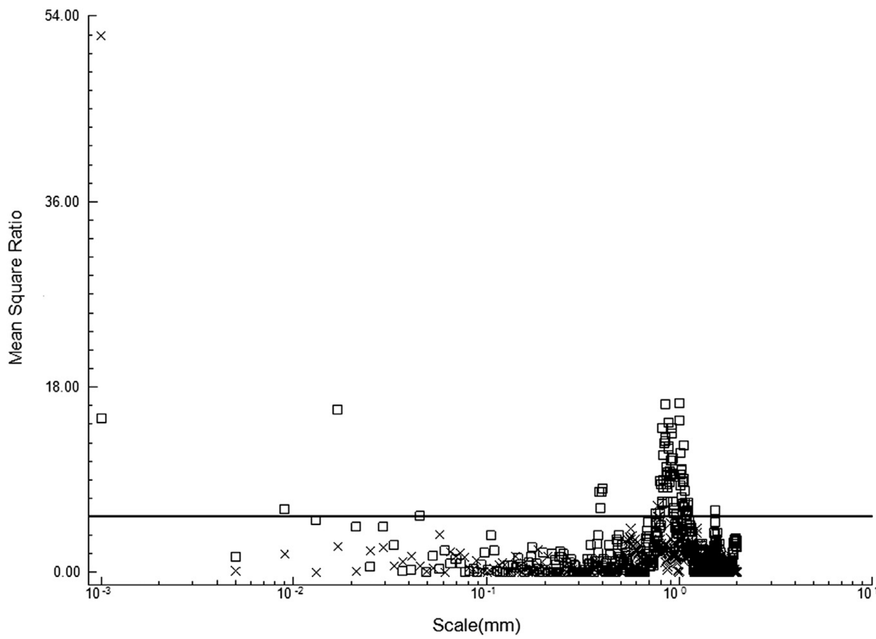

Fig. 11. *F*-test results (MSRs) of the mean relative lengths (RLs) versus scale for the six profiles in the near (used) regions (□) of the two flint flakes used on shell versus the two flint flakes used on dry antler and the six profiles in the far (unused) regions (×) of the two flint flakes used on shell versus the two flint flakes used on dry antler. The horizontal line indicates 99% confidence level for discrimination.

7. Discussion and conclusion

This research into the quantification of lithic use-wear has produced a substantial amount of information concerning the characterization and discrimination of stone tool surfaces. Specifically, a measurement system like laser profilometry coupled with a scale-sensitive algorithm like relative length (RL) can provide reliable documentation of surface roughness that can be used to discriminate used from unused tool surfaces, as well as surfaces of tools used on different contact materials under experimental conditions. Yet, laser profilometry and RL demonstrate both advantages and limitations in terms of their application to stone tools.

Among the advantages of this method is that the polish produced on stone tools can be measured and that surface textures produced through contact with different materials can be discriminated quantitatively. These data essentially confirm what traditional use-wear analysts have long observed using traditional optical microscopy and have described qualitatively – lithic use-wear does vary by contact material type (i.e., Keeley, 1980). Second, when considering the pottery-sawing tools in the second experiment, this research also documents the progressive development of wear quantitatively. Moreover, the flakes used in all four experiments demonstrate that the method can work on tools made from different lithic raw materials and the specific stone types from which tools are made will affect wear production and characterization. These data, like those of Lerner (2007), Lerner et al. (2007), provide mathematical support for this kind of relationship. Third, the laser profilometer generated line scans relatively quickly with its acquisition rate of 100 points/s over distances of 2 or 4 mm and a resolution of 400–1000 points/mm. With this acquisition rate, a line scan could be taken in 20 s for measurement lengths of 2 mm and 40 s for lengths of 4 mm. The time needed for each line scan varied somewhat based on the roughness of the surface being measured and the profilometer's resolution; this variation in length of time was minimal.

However, certain difficulties noted while conducting these experiments were primarily due to the limitations of the laser profilometer. One issue associated with the use of the laser profilometer to measure stone tools was the working distance between the laser and the stage upon which the objects were positioned. The working distance limited the size of the objects that could be measured using this system; whole tools, such as large, thick celts, or thick metate fragments would potentially exceed the allowable working distance. For large lithic artifacts, surface replicas would be required (Banks and Kay, 2003; Beyries, 1981; Bienenfeld, 1995; Knutsson and Hope, 1984; Plisson, 1983) and the reliability of results using the profilometer would be strongly dependent on the quality of the replica of each tool's surface. In addition to the sizes of the tools, both the raw materials from which they are made and their edge and surface structures need to be considered. In particular, very dark materials, such as obsidian, and surfaces with significant inclinations or curvatures proved more difficult to measure with the laser, as noted above in Section 3.2.

Although the laser profilometer is effective for generating two-dimensional surface characterizations of stone tool microtopography, each line scan only records a limited amount of surface information, which may be fine for well-developed, homogeneously worn surfaces, but is potentially more problematic for wear which is differentially distributed or slow to develop, as discussed for the wood-sawing flakes in the second experiment. Because wear can be anisotropic, the line scans may not fully capture the characteristics of use-wear patterns on stone tool surfaces. Consequently, it may be that three-dimensional area scans of used surfaces, such as those produced by a laser scanning confocal microscope (LSCM) (see Evans and Donahue, 2008; Evans and Macdonald, 2011; Stemp and Chung, 2011; Stemp et al., 2012, 2013) would be better for documenting characteristics of wear that are directionally dependent. Although surface area scans can be produced using the laser profilometer, the measurement quality, specifically resolution, is generally inferior to that of other measurement systems, such as atomic force microscopy (AFM), variable focus microscopy (VFM), and laser scanning confocal microscopy (see Evans and Donahue, 2008; Evans and Macdonald, 2011; Faulks et al., 2011; Kimball et al., 1995; Stemp and Chung, 2011; Stemp et al., 2012, 2013). These systems provide micro- and nanoscale data for the documentation of surface structure and the analysis of wear features that exceed the resolution typically provided by profilometry systems. Line scans taken perpendicularly to the tools' edges might provide further surface roughness data that could be helpful in addressing issues associated with anisotropy and surface wear.

To better assess the potential use of this method for quantifying use-wear on lithics, additional results would be necessary. Future work would require experimentation and analysis involving a larger number of replicates used on more contact materials. Specifically, numerous experimental tools would need to be used for the same activities so there would be multiple examples of implements representative of each type of wear condition. Moreover, more line scans in both the used (near) and unused (far) regions of the tools are necessary for generating data for each wear condition.

Finally, it should be noted that the use of laser profilometry and RL have yet to be applied to archaeological specimens. As such, it is not known how effective the method is for documenting and discriminating wear on tools that were used in the past. Although the results of the third and fourth experiments suggest this method should allow for quantification of use-wear on chipped flint artifacts, how post-depositional alteration of stone tool surfaces (Lévi-Sala, 1986, 1993, 1996; Burroni et al., 2002; see Evans and Donahue, 2005) would affect the documentation and discrimination of worn stone tool surfaces remains to be seen. This constitutes a major step in the development of the method before use-wear can be reliably documented on lithic artifacts.

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