Quantifying Use-Wear Polish Through 3D Imaging Software

First Results from a Preliminary Study Calculating Usage Time of Neolithic Sickles.

SEBASTIAN BOSTRÖM & JON LUNDIN

Abstract

Since its international development in the second half of the last century, use-wear studies have become an indispensable analytical method of archaeological research. The technique has often been criticized for basing results on subjective observations made by the researcher. The study presented in this paper uses an image analysis software to study the development of use-wear polish on flint tools. An initial case-study uses the software to measure polish development on experimental flint blades. Based on the results from this initial study a concluding case-study is conducted to calculate usage time of archaeological flint sickles.

Introduction

The implementation of use-wear studies in archaeology have made immensely important contributions to our understanding of prehistoric societies (Semenov 1964). Traces from tool-use such as striations, fractures, flake scars, edge-rounding, and polish can reveal what part of, and in what way an artefact was used, and what material the artefact was used on (Spurell 1892; Semenov 1964; Keeley 1980; Mansur-Franchomme 1983; Jensen & Petersen 1985; Knutsson 1988; Ibáñez *et al.* 2016). Information gathered from use-wear may be used to disclose function, organization and economies of archaeological sites, thus, bringing the archaeologist closer to revealing the activities of prehistoric societies. Today the technique is a re-occurring element in contract archaeology as well as more research-oriented excavations. However, the method has until only recently been limited to the fact that it is not able to produce quantitative data. Instead, results are often based on the knowledge and experience of the researcher (Taipale 2012; Marreiros *et al.* 2015). Therefore, many researchers have regularly expressed an interest in developing a more objective research method (Knutsson 1988; Grace 1989; Gonzales-Urquijo & Ibáñez 2003; Vardi *et al.* 2010; Linton *et al.* 2016; Kimball *et al.* 2017). Recent studies have explored the potential of image analysation software in the field of use-wear studies. While some have used software to provide data to expand on the discussion of the introduction of cultivated cereal in the Near east (Ibáñez *et al.* 2016), other studies have examined the role of raw materials effect on use wear development (Lerner 2007; Lerner *et al.* 2007; Lerner 2014a). Other studies have, through the use of lasers, been able to gather quantitative data regarding use-wear polish (Vardi *et al*. 2010). However, most of these studies have relied on new and advanced equipment such as confocal microscopes (Ibáñez *et al*. 2016; Pante *et al.* 2017). In this paper the authors suggest a method which is based on already established systems. An inverted metallurgical microscope with a magnification of 100 x to 200 x was used to document and photograph use-wear polish on archaeological, bifacial flint sickles and experimental flint blades. Using the image analysation software Mountainsmap®, a 3D-microtopography surface was created and analysed using ISO standards for roughness, flatness and height.

The study presented in this paper is a preliminary one, aimed to further testing the potential of Mountainsmap when studying changes in the micro topography of flint tools. Should the software be able to provide a way of extracting quantitative data regarding changes in distribution of use-wear polish over time used, the authors will attempt to measure the usage time of a selection of archaeological flint sickles.

Flint sickles

Tools intended for cutting have been used throughout all prehistoric periods. Since a usable edge is the only requirement for a cutting tool, there are many examples of unmodified flakes used for the same purpose as modified lithic tools (Steensberg 1943; Wyszomirski 1979; Knutsson 1988, Jensen 1994). Bifacial, one-piece flint sickles are known in Scandinavia from the late Neolithic period to the early Bronze Age (2350-1500 cal. BC) (Karsten 1994; Apel 2001; Persson 2007; MacClendon 2015). Unlike flint daggers, which in many cases can be found as funerary goods in graves, the flint sickles are mostly found in caches deposited in peat bogs, near large boulders or in crevices. The archaeological context in which these sickles have been found have led studies to associate them with ritualistic behaviour (Burenhult 1999, 375). This theory suggests that the deposited sickles should be seen as offering, most likely related to harvest. Regarding the typology of the sickles, Vang Petersen (1993, 138 f.) suggests a morphological change over time; from crescent shaped sickles during the late Neolithic to straight edged in the late Neolithic/early Bronze Age and a biconvex shape, with only rarely saw-toothed edge, during the early Bronze Age. Finally, during the late Bronze Age, sickles are made on heavy flint blades (Högberg 2009). Relatively little has been written on the subject of Neolithic flint sickles from Scandinavia, their exact function is somewhat debated (Jensen 1994) and it should be clarified that this is not the focus of this paper. The archaeological sickles used in this study display a polish most commonly generated when working siliceous materials such as grass, cereals, branches or reeds (Steensberg 1943; Jensen 1994; Högberg 2016). Therefore, to create comparable polish on flint blades - reeds will be used in the experiments presented in this paper.

Mountainsmap

Mountainsmap is an image analysis software developed by Digitalsurf. Compatible with most microscopes such as confocal-, scanning probe- and scanning electron microscopes, the software is, among other things, capable of rendering high quality 3D images from 2D microscope photos using the grey values of the pixels. Greyline values (GL) determine the brightness of the pixel with values ranging from 0 (black) and, in this case, 255 (white) (see Lerner 2014a). Mountainsmap also offers a variety of plug-in tools that can be used to analyse the texture and surface of the microscopic landscape. Though most commonly used in material science studies, the software has recently been used for archaeological purposes. One study utilised the software to identify surface modifications on archaeological bones. In the study, the authors managed to distinguish between modifications created by different actors and effectors (Pante *et al.* 2017). Similarly, researchers have been able to use Mountainsmap to differentiate carving techniques and tools used when creating Neolithic stone stelae discovered in Catalonia (Moitinho de Almeida *et al.* 2013). The study mentioned earlier in this paper by Ibáñez *et al.* (2016) uses a similar software, Sensomap, also developed by Digitalsurf but designed and restricted to Sensofar instruments.

Aims

Through methods similar to those developed by Lerner (2007; 2014a) and Ibáñez *et al.* (2016), this study will utilize an inverted metallograph microscope with a magnification of 200x together with the image analysis software Mountainsmap to gather quantitative data concerning use-wear on experimental flint sickles. As this is a preliminary study, restricted in time and budget, only one type of use-wear will be studied – polish (see Lerner 2014a). The aim is then to use this quantitative data to discuss a correlation between time of usage and the development of polish. The final part of this study will be dedicated to measure usage time of a selection of bifacial archaeological flint sickles.

Theory and method

When using flint tools to cut silica rich plants like cereals, grass or reeds, the edge of the tool develops a fine polish. The cause of this polish has long been subject of research. Whilst some experimental studies claim that this polish is a result of a chemical reaction between the flint and the worked material, others claim that the polish actually consists of residues from the plants that, through use have accumulated and hardened on the tool edge (Witthoft 1967; Anderson 1980; Kaminska-Szymaczak 2002; Anderson *et al.* 2006). Other theories state that polish is developed by the smoothing of the flint surface from the friction generated between the flint tools and the worked material (Korobkova 1996; Rosen & Shugar 2007). Studies have also shown that there are other factors that affect the rate at which polish is developed, including the lithic raw material itself (Lerner *et al*. 2007). Silica, found in organic as well as inorganic material acts as a polishing agent to further help develop polish on flint (Fullagar 1991; Jensen 1994). Other studies have shown that when cutting or working plants, the thickness and the moisture of the plants affects the build-up rate of the polish. Therefore, cutting plants that are thicker and containing more moisture produces polish at a higher rate than when cutting plants that are thin and dry (Unger-Hamilton 1991). Characteristics of the lithic also affect the rate to which polish is developed. Studies carried out by Lerner have proven that hardness and the surface roughness of the raw material greatly affect the development of not only polish, but of all use-wear (Lerner *et al*. 2007; Lerner 2014a; Lerner 2014b). By the theories stated above, polish development is relative to tool usage time. The longer a tool is used, the more polish it acquires and over time the polish built up from cutting silica rich plants increases until, finally the edge is completely altered and highly glossy. As mentioned above, this study will use reeds to create use-wear polish comparable to that on archaeological sickles. However, the authors are aware of the notable differences between polish development from reeds and cereal (Ibáñez *et al.* 2016), as well as the differences in moisture levels between plants. Also, worth mentioning is that the experimental blades used in this study were un-hafted, a condition which also affect applied force and therefore also the development of use-wear (Broadbent & Knutsson 1975). The aim of this study is not to determine the function of the archaeological sickles but simply, through experiments create use-wear polish similar to the use-wear polish found on archaeological flint sickles and finally study it. An additional methodical problem regarding this study is the difference between the microscopic topography of the bifacial sickles themselves and the experimental blades, which may affect the build-up of polish and by extension the estimated usage time in this study. Image analysis software has considerable potential for application in archaeological use-wear research. Researchers, by applying different software, have not only been able to distinguish between different use-wear on tools used in prehistoric societies, but have also found a way to present these results in quantitative form. Since quantitative data can be gathered regarding polish distribution, then, if sufficiently tested it should be possible to measure a tool's usage time using the amount of, and distribution of polish. To test the theory, standard parameters for height and flatness set by ISO (International Organization for Standardization) as well as furrows of the microscopic landscapes of experimental, as well as archaeological flint tools were studied - since these, as stated by previous studies (Lerner 2014a; Lerner 2014b) have been subject to change over time of use. Following is a brief presentation of the parameters used in this study (For further details on ISO parameters see www.iso.org).

- Root mean square height (Sq) is used to define the mean height of the studied surface.
- Maximum peak height (Sp) defines the height of the highest peak within the analysed area.
- Arithmetic mean height (Sa) is used to calculate roughness of the studied surface by comparing differences between peak values and the mean height of the studied microscopic surface.
- Peak to reference flatness deviation (FLTp) is the value of the largest positive local flatness deviation from the least squares reference plane.
- Root mean square flatness deviation (FLTq) is the square root of the sum of the squares of the local flatness deviations from the least squares reference plane.

In order to study the image captured via the microscope's camera as a surface the image has to be three-dimensional in Mountainsmap. This is done utilising the "convert into surface"-tool. This process creates a 3D surface using the greyline levels of the image. This was done with the setting to "convert into surface" and using "PAL standard" under "luminance standard". Technically, the 3D surface created through the heretofore presented process was usable to carry out the study, but to reach more accurate results – further adjustments were made. When studying height parameters, ridges and protrusions of the object surface can distort the results. Moreover, since light from the microscope is focused on the centre of the examined area - a false curvature of the image can be created. To manage these issues, and to remove the general slope of the image, which also might affect the results - the software is equipped with a tool called "levels" which, as the name suggests, levels the "studiable" (the studied image). By using the least squares plane of the surface, this tool creates a horizontal image. Using optical microscopes can through measurement errors falsely create peaks and depths on the studied surface. The "remove outliers" tool adjusts these errors by isolating and removing these irregularities. Though necessary, using this tool creates holes in the "studiables". If left uncorrected, these non-measured points could affect the final results of the study, therefore the "fill NM points" tool was used. To minimize the risk of corrupting the final results, this tool uses values of the area adjacent to the empty points to fill in the missing data. Since the aim of this study is to examine the development of micro-polish – roughness rather than waviness of the surface texture was isolated and put through the next step of the analysis. The tool "standard filter" was applied to separate the waviness from the roughness of the "studiables". From the "studiables", a 200 x 200 µm area was selected by using the "extract area" tool. In choosing what area to analyse the authors referred to the same methods used by earlier researchers (see Gonzales-Urquijo & Ibáñez 2003; Lerner 2014a; Lerner 2014b; Ibáñez *et al.* 2016). While extensive polish was sought after, the authors tried to avoid ridges and other irregularities that could distort the results. This step concludes the preparation phase and the "studiables" were now ready to be analysed. In the first part of the "study phase" parameters concerning height and flatness were calculated using the tool labelled "parameters table" in the "studies" toolbar. This tool calculates surface textures of form parameters according to ISO and national standards. In this study the ISO 25178 standard for height and the ISO 12781 standard for flatness was used. The second and last step of the study phase is to calculate depth and density of valley networks of the microtopography. This was done using the "furrows" tool.

Case study 1: Experimental blades

In the first case study, polish development on experimental flint tools were studied. For this purpose, 10 flint blades, knapped from a single core by the late Danish flintknapper Thorbjørn Petersen were selected. In addition to this, one blade was added as an unused blade with an unmodified surface for reference. The size and shape of the blades was crucial when selecting what blades to choose for the experiment. Longer blades (around 10 cm or over) proved easier to hold and provided a longer cutting edge which in turn allowed for longer strokes. Each blade was then used to cut fresh winter reeds (Phragmites communis) for different periods of time. Some very notable observations of polish development from cutting reeds have been made in previous studies (Vaughan 1985; Jensen 1994; Osipowicz 2019). Reeds are generally rich in silica but compared to other plants, the degree of silica found in reeds can sometimes differ. How much they differ seems to be a question of local variation in that reeds growing in a damp environment contain more silica than reeds growing in a dryer environment (Jensen 1994). As noted in the previous chapter, micro-wear derived from cutting fresh silica rich plants with flint is unique in that it leaves a prominent polish on the tool edge. Jensen (1994) also states the importance and usefulness of the plant in that it can be harvested year-round and have multiple applications. Considering its richness in silica and its well documented prehistoric use – reeds were deemed a suitable experimental material. Being that this study was conducted during the winter, the authors were aware of the potential problem with cutting dry, not silica rich material and how it differs from cutting fresh, silica rich material. The reeds grew in a lake, still not completely frozen and therefore had retained some of its moisture. Also, temperatures were relatively high and well above freezing. Due to the requirement to easily prepare the blades for studying under the microscope, temporarily hafting methods, like the Broadbent and Knutsson method (Broadbent & Knutsson 1975) was not an option. Instead, the experiment used non-hafted blades. However, it is worth noting that the hafting technique itself is not in focus in this experiment and that recent studies suggest it is not statistically possible to distinguish differences between individual users in microwear polish due to un-hafted lithics (Key 2013).

Since this study aims to compare polish development and distribution between experimental tools and archaeological tools, a uniform mechanical motion was favourable. In keeping with the results from Steensberg's (1943) experiments, that hafted flint sickles were used in a cutting motion, the authors settled on cutting rather than sawing. To obtain a database of the gradual increase of silica polish the usage time was increased by 30 minutes for each flint blade starting with blade no. 2 at 30 minutes and finishing with blade no. 11 at 5 hours. Initial experimentation revealed that harvesting the reeds and storing them indoors prior to cutting rendered the reeds dry and hardened. Cutting the reeds in this dried-out state left little to no polish and greatly damaged the tool edge. Use-wear left on these flint blades bear a close resemblance to those associated with woodworking. Thus, it was concluded that cutting the reeds outdoors, whilst still fresh would produce results better suited for studying. Over the course of three days in early February 2019, winter reeds were harvested in Uppsala Sweden.

The reed stems had a yellow, rather tough outer layer, while the core of the reeds had retained more moisture and displayed a more greenish colour. Also, the reeds varied in thickness between approximately 0.5 to 1 cm. Unfortunately, there were no means available to measure moisture of the worked material for this study. Since these experiments were carried out by two individuals, a tempo of approximately one cut per second was set to ensure uniformity. Initially the blades cut through the reeds without the use of force, but a noticeable loss of sharpness of some blades was recorded at around 30 minutes of cutting. From this point on, cutting of the reeds became more difficult and damage to the edge was clearly visible. The dullness of the blades was further increased throughout the course of use until at around 4 hours when the edge of the blade was so dull that it was no longer possible to cut into the reeds without using noticeable muscle strength. Similar observations have been recorded by other researchers (Dubois 2015). The need to use noticeable muscle strength to cut the reeds is something the authors got to experience during the cutting process of blades number 10 and 11, which lasted for 4.5 hours respectively 5 hours of cutting. Once the cutting process was completed, the next step was to clean and photograph each blade.

Cleaning and photographing

When cleaning archaeological or experimental tools it is important not to use methods or tools that can damage the material surface. Therefore, the experimental blades were first cleaned using hot water and soap (Marreiros *et al.* 2015; MacDonald and Evans 2014). Next, the authors used an ultrasonic cleaner since it is deemed gentler than using chemicals such as NaOH and KOH. It is still unclear how these dissolvents affect silica polish on flint but some studies have debated that they can change the structure of the use wear polish (Andersen & Whitlow 1983; Banks 2004). Instead, smudges from handling and more resilient impurities left on the blades were cleaned with 99.5% ethanol. Since contact with metal can damage the tool edge or surface rubber tweezers were used when handling the blades (Marreiros *et al.* 2015). Prior to photography, the authors recorded characteristics of the blades. Sharpness, damages, what edge had been used, degree of gloss displayed, and length of consistent polish was documented. The length of the polish of each blade was measured using a digital calliper and anomalies such as extensive edge wear was noted using 100x magnification.

Studies have shown that ridges and bulges of the tools are more intensely in contact with the worked material and will thus be more affected by use-wear (Gonzales-Urquijo & Ibáñez 2003). This means that polish is developed to different degrees on the blade depending on its morphology. Therefore, it was determined that in order to produce the most objective results, a larger quantity of "studiables" representing different areas of the blades would have to be analysed. Using a Nikon Epiphot, inverted metallograph microscope with a magnification of 200x, 3 pictures were taken on the dorsal side of each blade. First, one photo was taken in the centre of the polished area. Then, two photos were taken at the halfway-points between the centre and both edges of the polished area (see fig. 1). The study had to diverge from this process when ridges or damages to the flint surface would obscure the photographs. To compensate and to make photographing areas with limits in depth of field possible, NIS Elements (a software used to acquire images through the microscope) has an EDF (extended depth of focus) process. As its name would suggest, this function takes numerous photographs, with different focal length and stacks them to create an image with greater depth of field. Once all the blades were photographed, the pictures were imported into Mountainsmap where they could be used to generate quantitative data.

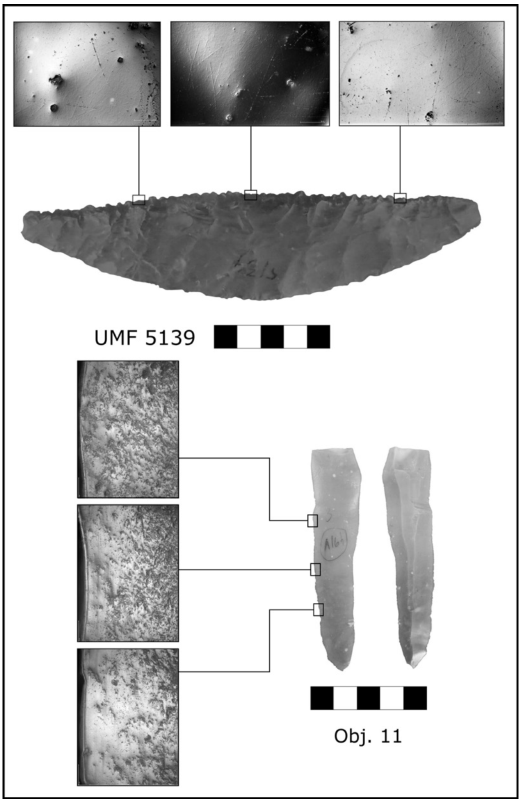

Fig. 1. Strategy for acquiring samples from the archaeological sickles (above) and experimental flint blades (below). Scalebar length 5 cm.

Obtaining quantitative data through Mountainsmap

Once imported to Mountainsmap, all blades were analysed following the procedure presented above (chapter theory and method). In order to select the area of the image containing most polish when using the "extract area" tool, some trial and error was needed. This was especially true with images taken of blades with low amounts of polish (blades: 2-3). Polish on these blades were scarce and scattered, making determining what areas were most polished difficult. However, by repeating this step, the most polished area could finally be extracted and put through to the next phase. By using ISO standards for height and depth, parameters concerning the microscopic landscape of the experimental blades were calculated. The

Object Experimental	Time (H)	Mean Depth of Furrow	Root-mean-square height	Maximum peak height	Arithmetic mean height	Peak to reference flatness deviation	Root-mean-square flatness devitaion	Sum	Divided by number of paramters	Mean value (sum)
Blade 2	30	110.6	56.7	153.6	47.4	140.3	59.8	568.4	6	94.73333333
Blade 3	60	92.5	51.8	103.2	46.1	91.4	52.3	437.3	6	72.88333333
Blade 4	90	79.6	53.2	94.1	45.6	80.1	53	405.6	6	67.6
Blade 5	120	79.2	58.8	85.3	48.6	64.5	57.2	393.6	6	65.6
Blade 6	150	61.6	49.6	89.1	39.9	66.7	48.1	355	6	59.16666667
Blade 7	180	62.4	48.4	79.6	40.4	67.26	47.7	345.76	6	57.62666667
Blade 8	210	61.1	41.9	73.1	36.4	60.2	41.4	314.1	6	52.35
Blade 9	240	65.5	39.1	70.4	34.7	60.4	39.1	309.2	6	51.53333333
Blade 10	270	51.6	34.8	72.6	30.6	57.9	33.8	281.3	6	46.88333333
Blade 11	300	26.7	24.8	45.5	17.6	27.6	23.4	165.6	6	27.6
Object Archaeological	**Polish group**	**Mean Depth of Furrows**	**Root-mean-square height**	**Maximum peak height**	**Arithmetic mean height**	**Peak to reference flatness deviation**	**Root-mean-square flatness deviation**	**Sum**	**Divided by number of parameters**	**Mean value (sum)**
UMF 922	3	110.9	75.5	129.3	66.53	123	74.8	580.03	6	96.67167
UMF 928	3	106.56	60.43	112.53	53.73	103.03	60.36	496.64	6	82.77333
UMF 930	3	102.9	49.6	181.33	38.96	153.33	54	580.12	6	96.68667
UMF 535	4	88.3	56.7	106	48.9	98.63	56.53	455.06	6	75.84333
UMF 539	4	92.03	60.43	96.86	53.5	88.06	61.03	451.91	6	75.31833
UMF 4965	5	41.7	32.26	84.5	27.6	76.76	35.9	298.72	6	49.78667
UMF 5312	5	45.83	38.13	50.23	25.3	39.86	37.93	237.28	6	39.54667
UMF 532	5	53.6	36.7	67.43	31.93	57.96	36.8	284.42	6	47.40333
UMF 537	5	57.63	48.66	82.96	37.3	66.33	49.36	342.24	6	57.04
UMF 538	5	49	41.8	65.1	33.7	58.93	42.3	290.83	6	48.47167
UMF 932	5	45.3	42.16	60.46	27.66	49.86	42.3	267.74	6	44.62333
UMF 3073	5	51.36	42.13	59.2	31.96	54.5	43.1	282.25	6	47.04167
UMF 3069	5	49.53	41.56	72.63	32.16	58.56	43.46	297.9	6	49.65
UMF 4637	6	15.53	15.96	53.16	10.11	44.05	20.63	159.44	6	26.57333
UMF 5139	6	6.07	8.48	36.4	5.11	25.16	12.51	93.73	6	15.62167
UMF 3071	6	19.97	18.4	42.8	11.55	33.26	18.6	144.58	6	24.09667
UMF 4019	6	28.53	24.66	30.06	12.22	19.26	24	138.73	6	23.12167
UMF 3067	6	9.36	12.43	11.89	4.03	8.42	12.31	58.44	6	9.74

Table I. Summation of raw data from the experimental blades and archaeological sickles.

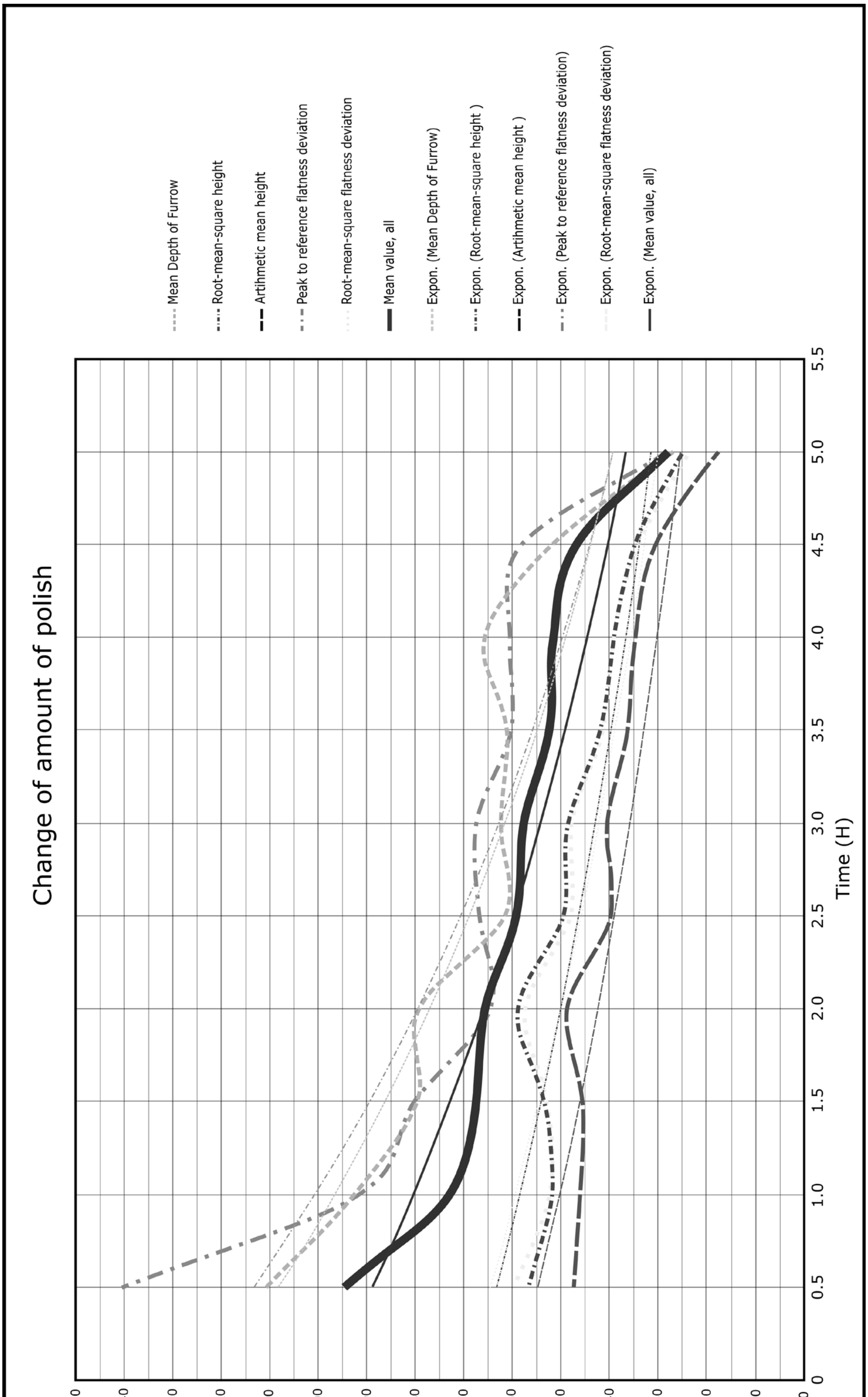

Fig. 2. Changes in the studied parameters of the experimental blades. Note the reduction of height value over time.

parameters: mean depth of furrows, root-mean-square height, arithmetic mean height, peak to reference flatness deviation and root-mean-square flatness deviation for each image was imported to a single chart (Table I). The X-axis of this chart represents object number and time of usage from 0,5h to 5h, and the Y-axis represents height (GL).

Results

Data gathered through the study phase of case 1 shows a reduction in height and depth value (GL) over time used (Fig. 2) this confirms the theory that use-wear polish is a result of smoothing of the lithic surface. Upon closely examining the height parameters for each individual blade, some inconsistencies were noted. Shifting results from images taken of the same object can again be traced to variations of the microscopic topography (Vardi *et al*. 2010).

Constructing an experimental time trend line

To create values more representative of the actual surface, and to manage the irregularities noted above, the data gathered through Mountainsmap were used to calculate mean height values for all experimental blades. From the mean height values the following exponential trendline was calculated: R^2=0.8417. Following this curve of development would imply that usage-time is only quantitative through use-wear polish up to around 24 h. Still, case study 1 showed that, due to the rapidly deteriorating quality of the cutting edge, retouches had to be done to the tool's edge in order for it to properly function for longer periods of time. As stated by other researchers the rate of this loss in sharpness is probably related to the angle of the cutting edge and the contact surface (Dubois, 2015, Jensen 1994). Another factor relating to the loss in sharpness of the edge is quality of the flint. Finely grained flint develops polish at a higher rate than coarser-grained flint. Therefore, when compared to a tool made from a coarse-grained flint, a finely grained flint tool will dull more readily (Balcer & Schild 1980; Levi-Sala 1996; Quintero *et al.* 1997; Unger-Hamilton 1983; Unger-Hamilton 1988).

Case study 2: Archaeological sickles

After establishing that polish development is relative to usage time, the authors attempted to calculate usage time of archaeological flint sickles. For this case study, 32 archaeological objects listed as sickles were borrowed from Gustavianum museum in Uppsala, Sweden. The context from which these sickles stem is unknown, but they can be typologically linked to the Neolithic and early Bronze Age of Scandinavia (Steensberg 1943; Apel 2001; MacClendon 2015). Initial sorting involved discarding sickles not displaying any visible polish from the study. Moreover, one sickle (UFM 939) was not included in this study since uncertainties regarding its labelling arose upon inspection. Saw-toothed objects (UFM 4965; UFM 5139) that in some cases have been labelled as saws were not discarded since it has been argued that these objects are in fact sickles (Apel 2001). From the originally 32 archaeological objects listed as sickles, 18 bifacial flint sickles showed visible polish and therefore were chosen for this study and furthermore examined using the same procedure as with the experimental blades in case study 1. Since these sickles have been a part of the museum's collection for decades, they have undoubtedly been touched and handled by the museum's staff. Therefore, the sickles were put through the same cleaning process as the experimental blades. Once clean, the authors noted the shape, colour, patina, condition and raw material (finer grained/coarser grained) of the archaeological sickles.

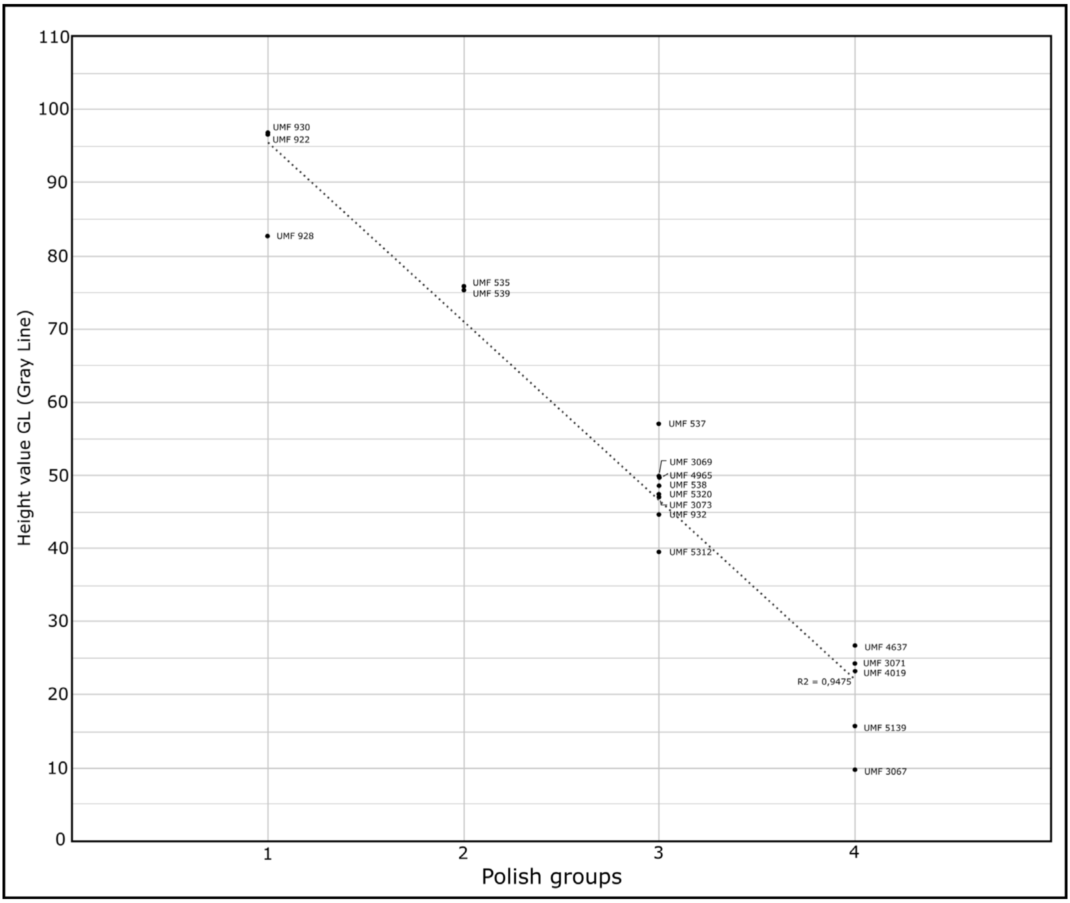

Fig. 3. Mean height values of the archaeological sickles in relation to their relative polish group and the calculated trendline.

To get a general understanding of differences in polish development between the sickles they were divided into 4 different groups by gloss. This was done on a macroscopic level with group 1 displaying a moderate amount of gloss and group 4 being excessively glossy (see fig. 3). It was here assumed that the sickles displaying more gloss had more use-wear polish and therefore more extensively used than those with less (Spurell 1892; Meeks *et al.* 1982; Vardi *et al.* 2010). When photographing the sickles, three areas were selected (left, middle and centre) on the most polished edge of the bifacial sickles. Since the microtopography on the bifacial sickles vary, due to knapping technique and raw material, in a greater variation in comparison with the experimental blades the authors focused on highly polished horizontal areas while avoiding ridges and irregularities. Images of the archaeological sickles were then corrected and prepared using the same method as with the experimental blades. The same parameters (mean depth of furrows, root-mean-square height, arithmetic mean height, peak to reference flatness deviation and root-mean-square flatness deviation) calculated in case study 1 were gathered from the archaeological sickles.

Results

As with the experimental blades, to obtain results more representative of the whole objects - height parameters gathered during the study phase were used to calculate mean height values of all the archaeological sickles. Following this, the mean height values were compared to the observations made during the macroscopic examination by creating a chart displaying mean height (Y-axis) and group (X-axis) (Fig. 3). The quantitative data confirmed the results from the visual observations in that the GL value decreased from group 1-4. Sickles displaying more gloss and with more polish have a lower GL value than sickles with less gloss and polish. Due to a limited number of archaeological sickles, fragmented sickles were not excluded from this study, even though inconsistencies in polish development between the proximal and distal ends of the original sickles could affect the mean GL value. The next step of the study was to compare the quantitative data gathered from the experimental blades with the data gathered from the archaeological flint sickles.

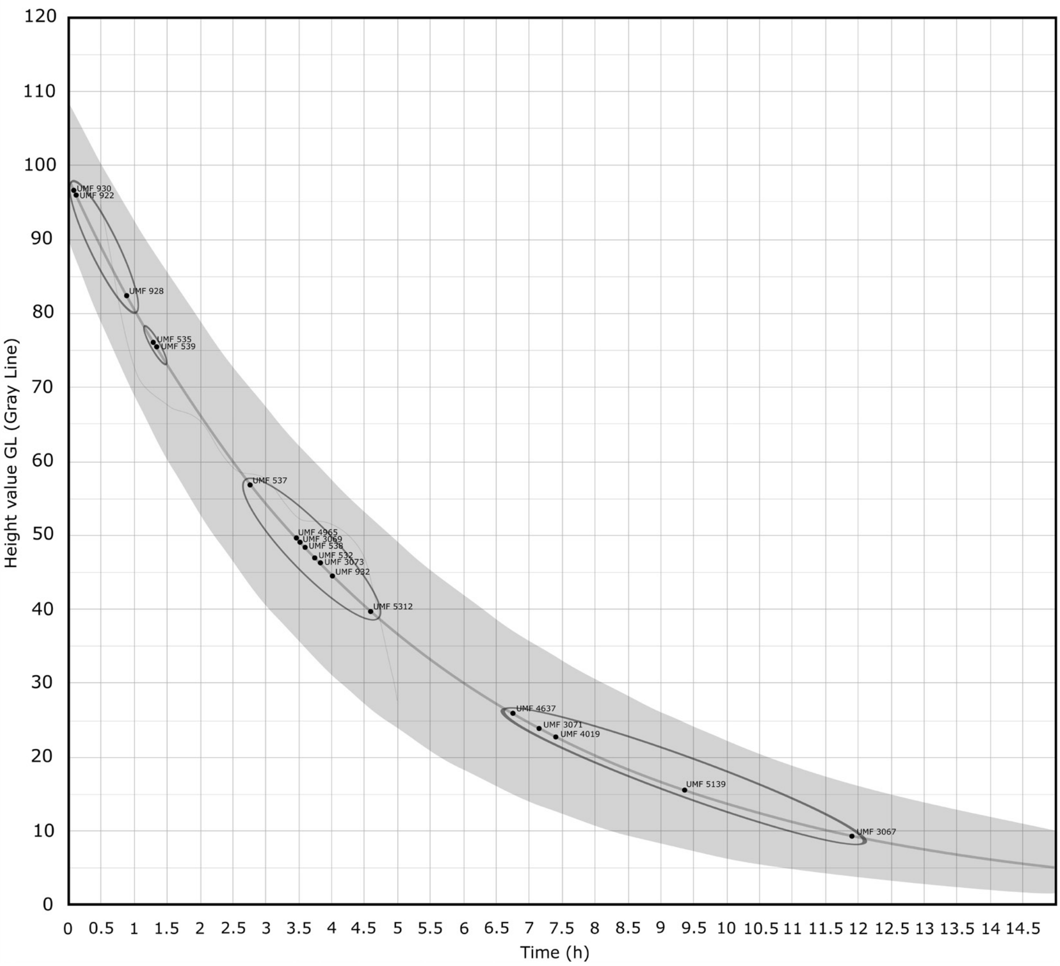

Fig. 4. Estimated usage time of the archaeological flint sickles. Grey area indicating margin of error of the usage time.

Comparing quantitative data from case study 1 & 2

To calculate usage time of the archaeological sickles the quantitative results gathered in case study 2 was imported to a chart with the exponential trendline established in case study 1 (Fig. 4). Using mean GL value to place the archaeological sickles on this trendline confirmed the observations made during the macroscopic examination in that it placed the groups in ascending order from left to right in the chart. Interestingly, the GL of the sickles in group 4 placed them between 6.5 and 12 h usage time, well over the usage time of the experimental blades.

Discussion

It should be noted that this is only a preliminary study and the authors are aware of many factors that can affect the results from this study. As noted by Ibáñez *et al.* (2016) polish developed by cutting reeds differ from that developed when cutting cereals. Being that the degree of moisture of reeds is higher than that of ripe cereals, reed polish develops quicker than ripe cereal polish. Another problem with the comparability between the experimental and archaeological polish should be noted when studying the sickles with an estimated usage time exceeding 5 hours. Since the experiments presented in this study only cover usage times up to 5 hours, the sickles that exceed this time limit should be seen as estimates. And while R^2 =0.8417 is an acceptable trendline value, it might be affected by some external factors as mentioned above. Reeds of a higher maturity contain more moisture and would therefore lead to a rapid build-up of polish (see above). As noted in case study 1, quality of the flint also affects the rate to which polish accrues. Finely grained flint produces polish at a higher rate than a coarser-grained flint (see above), which also tend to dull the blade in use. The experimental blades of this study all come from the same core, which differs from the variety of the archaeological sickles in terms of raw material and thus also the microscopic surfaces. This is a methodological problem the authors are aware of, and it may affect the results of this study. However, the analysed areas extracted from the microscope pictures in this study strives to focus on areas with proper polish build up. As noted during this study, polish build up on flint surfaces tend to smooth the contact area down whether it be fine-grained or coarse-grained flint. It is worth noting that the aim of this study was not to test how/if use-wear polish differs on fine-grained/coarse-grained flint. While the utilization of Mountainsmap seems to be a viable way to quantify use-wear polish, the researcher cannot be excluded from the analytical process. Impurities, cracks and ridges must be manually excluded from the study since there is no way for the software to automatically distinguish between these and striations or other use-wear. With more time and resources, a more thorough study concerning polish development could be conducted. Using a confocal microscope would enable the whole surface to be analysed in one session since the image created in a confocal microscope is not limited to a topographic sample generated from individual photographs via an optical microscope (Marreiros *et al.* 2015). This would produce a greyline value better representing the actual polish. Furthermore, increasing the number of experimental blades or studying the development of polish on one blade instead of 10, taking photographs every 30 minutes would produce more reliable results. Moreover, since the trendline calculated in case study 1 reaches a stationary point at around 24 h it would be interesting to conduct experiments exceeding this time in order to test trendline. As stated above there are many factors which affect the development of use-wear polish and regardless of the number of experiments, tools and digital equipment provided the result will still be an estimation of usage time.

Conclusion

The preliminary study presented in this paper has shown that it is possible to gather quantitative data regarding use-wear polish using Mountainsmap and photographs taken with a camera mounted inverted metallographic microscope with a magnification of 200x. Results from case study 1 has also shown that the development of use-wear polish relates to time used. In proving this, case study 1 also provides a way of calculating relative usage time. Results gathered in case study 2 shows that development of polish correlates to the amount of gloss accrued from the flint sickles.

Provided that conditions that affect the development of polish (used materials, amount of moisture, stroke rate, applied pressure, etc.) are the same when using the experimental blades as with the archaeological sickles - it is possible to measure how long the archaeological sickles have been used by the prehistoric societies from which they derive from. Since these conditions cannot be properly controlled the usage time of the archaeological sickles measured in case study 2 should be regarded as an estimate and the graphs provided in this article should not be used to calculate an exact usage time of flint sickles.

It can be discussed that by combining use-wear studies with the method presented in this article archaeologists can restore some of the cultural identity the objects have lost since being deposited. Being able to calculate how much a single object has been used also allows for extensive comparative studies. The next step in this study will apply the method used in case study 1 and 2 with a confocal microscope. The confocal microscope will provide data which will help to further understand how use-wear polish is developed which ultimately could allow more exact calculations of usage time of archaeological tools. Expanding on this study could potentially enable quantitative data to be gathered from other types of use-wear, such as striations or flake scars. Further experimentation could also enable to not only differentiate between different types of worked materials but also different types of tools - such as scrapers, adzes or burins. Traditionally, the bifacial Danish sickles would be hafted. How use-wear polish pertains to force is in this case unclear, but hafting the sickles should have some effect on polish build-up. Further experiments should therefore also focus on using temporary hafting techniques like Broadbent and Knutsson (1975).

Acknowledgement

Firstly, a very special thanks to Helena and Kjel Knutsson at Stoneslab for their support and encouragement. Without their guidance, this study would not have been possible. Thanks to John Worley and Gustavianum museum for allowing us to study their lithic artefacts. We would also like to thank Anne Berger at Digital surf for enabling this study by providing us with a trial membership of Mountainsmap.

References

Andersen, H. H. & Whitlow, H. J. 1983. Wear traces and patination on Danish flint artefacts. *Nuclear Instruments and Methods in Physics Research*.

Anderson, P. C. 1980. A testimony of prehistoric tasks: diagnostic residues on stone tool working edges. *World Archaeology* 12 (2).

Anderson, P. C., Georges, J.-M., Vargiolu, R. & Zahouani, H. 2006. Insights from a tribological analysis of the Tribulum. *Journal of Archaeological Science* 33 (11).

Apel, J. 2001. *Daggers, Knowledge and Power. The Social Aspects of Flint-Dagger Technology in Scandinavia 2350–1500 cal BC*. Kust-till-kust böcker 3. Uppsala.

Balcer, B. & Schild, R. 1980. Traces of wear and stone tool function: do they reallymean what they show? In Schild, R. (ed.), *Unconventional Archaeology: New Approaches and Goals in Polish Archaeology*. Polska Academica Nauk, Inastitute Historii Kultury Materrialnej, Wroclaw.

Banks, W. E. 2004. *Toolkit structure and site use: Results of a High-Power Use-Wear Analysis of Lithic Assemblages from Solutré (Saône-et-Loire), France.* University of Kansas.

Broadbent, N. & Knutsson, K. 1975. An experimental analysis of quartz scrapers: results and applications. *Fornvännen* 70.

Burenhult, G. (ed.) 1999. *Arkeologi i Norden 1*. Stockholm.

Dubois, J. J. 2015. *Differential Development of Sickle Polish Due to Moisture Content of Herbaceous Plant Material*. University of Arkansas.

Fullagar, R. L. K. 1991. The role of silica in Polish formation. *Journal of Archaeological Science* 18 (1).

Gonzalez-Urquijo, J. & Ibáñez, J. J. 2003. The quantification of use-wear polish using image analysis. First results. *Journal of Archaeological Science* 30 (4).

Grace, R. 1989. *Interpreting the Function of Stone Tools: The Quantification and Computerization of Microwear Analysis*. British Archaeological Report, International Series 474. Oxford.

Högberg, A. 2009. *Lithics in the Scandinavian Late Bronze Age: Sociotechnical change and persistence*. British Archaeological Report, International Series 1932. Oxford.

Högberg, A. 2016. Microdenticulates of the funnel beaker culture. Lithic attribute anlysis, use-wear analysis and contextual analysis. *Acta Archaeologica* 87.

Ibáñez, J. J., Anderson, P. C., González-Urquijo, J. & Gibaja, J. 2016. Cereal cultivation and domestication as shown by microtexture analysis of sickle gloss through confocal microscopy. *Journal of Archaeological Science* 73.

Jensen, H. J. 1994. *Flint tools and plant working: Hidden traces of stone age technology*. Aarhus.

Jensen, H. J. & Petersen, E. B. 1985. A Functional Study of Lithics from Vænget Nord, a Mesolithic Site at Vedbæk, N.E. Sjælland. *Journal of Danish Archaeology* 4.

Kaminska-Szymaczak, J. 2002. Cutting Graminae tools and "sickle gloss" formation. *Lithic Technology* 27.

Karsten, P. 1994. *Att kasta yxan i sjön: en studie över rituell tradition och förändring utifrån skånska neolitiska offerfynd*. Stockholm.

Keeley, L. H. 1980. *Experimental determination of stone tool uses: a microwear analysis*. Chicago.

Key, A. J. M. 2013. Applied force as a determining factor in lithic use-wear accrual: an experimental investigation of its validity as a method with which to infer hominin upper limb biomechanics. *Lithic Technology* 38.

Kimball, L. R., Coffey, T. S., Faulks, N. R., Dellinger, S. E., Karas, M. & Hidrjrati, N. 2017. A Multi-instrument Study of Microwear Polishes on Mousterian Tools from Weasel Cave (Myshtulagty Lagat), Russia. *Lithic Technology* 42.

Knutsson, K. 1988. *Making and using stone tools: the analysis of the lithic assemblages from Middle Neolithic sites with flint in Västerbotten, northern Sweden. Appendices*. Uppsala.

Korobkova, G. 1996. The Blades with Mirror like Polishing: Myth of Reality. In Kozlowski, S. K. & Gebel, H. G. K. (eds.), *Neolithic Chipped Stone Industries of the Fertile Crecent, and Their Contemporaries in Adjacent Regions: Proceedings of the Second Workshop on PPN Chipped Lithic Industries, Studies in Early Near Eastern Production, Subsistence and Environment*. Berlin.

Lerner, H. J. 2007. *Lithic Raw Material Variability and the Reduction of Short-term Use Implements: An Example from Northwestern New Mexico*. British Archaeological Report, International Series 1688. Oxford.

Lerner, H. J., Du, X., Costopoulos, A. & Ostoja-Starzewski, M. 2007. Lithic raw material physical properties and use-wear accrual. *Journal of Archeological Science* 34 (5).

Lerner, H. J. 2014a. Intra-raw material variability and use-wear accrual: a continuing exploration. *Journal of Lithic Studies* 1 (1).

Lerner, H. J. 2014b. Intra-raw material variability and use-wear formation: An experimental examination of a Fossiliferous chert (SJF) and a Silicified Wood (YSW) from NW New Mexico using the Clemex Vision processing frame. *Journal of Archaeological Science* 48 (1).

Levi-Sala, I. 1996. *A Study of Polish on Flint Implements*. British Archaeological Report, International Series 629. Oxford.

Linton, J., Monna, F., Sestier, C & Martineau, R. 2016. Quantifying Cereal-Reaping Microwear on Flint Tools: An Experimental Approach. *Archaeometry* 58 (6).

MacClendon, B. E. 2015. *The Sickle's Edge: An Experimental Use-wear Approach to Investigating Sickle Deposition in Bronze Age Europe*. Theses and Dissertations. University of Wisconsin-Milwaukee.

MacDonald, D. A. & Evans, A. A. 2014. Evaluating Surface Cleaning Techniques of Stone Tools Using Laser Scanning Confocal Microscopy. *Microscopy Today* 22 (3).

Mansur-Franchomme, M. E. 1983. Scanning electron microscopy of dry hide working tools: The role of abrasives and humidity in microwear polish formation. *Journal of Archaeological Science* 10.

Marreiros, J. M., Gibaja Bao, J. F. & Ferreira Bicho, N. 2015. *Use-Wear and Residue Analysis in Archaeology*. Cham.

Meeks, N. D., Sieveking, G. de G., Tite M. S. & Cook, J., 1982. Gloss and Use-wear Traces on Flint Sickles and Similar Phenomena. *Journal of Archaeological Science* 9 (4).

Moitinho de Almeida, V., Rosillo, R., Barcelo, J. & Palomo, A. 2013. Linking 3D digital surface texture data with ancient manufacturing procedures. *2013 Digital Heritage International Congress (DigitalHeritage)*.

Osipowicz, G. 2019. Plant processing in the Late Mesolithic Poland: in search for function of the mysterious 'curved knives'. *Archaeological and Anthropological Sciences* 11.

Pante, M. C., Muttart, M. V., Keevli, T. L., Blumenschine, R. J., Njau, J. K. & Merrit, S. R 2017. A new high-resolution 3-D quantitative method for identifying bone surface modifications with implications from the Early Stone Age archaeological record. *Journal of Human Evolution* 107.

Persson, P. 2007. *Skäran i bäcken – En lösfyndsstudie om möjliga senneolitiska offerfynd på ön Hven*. Master's thesis, Lund University.

Quintero, L. A., Wilke, P. J. & Waines, J. G. 1997. Pragmatic studies of near Eastern Neolithic sickle blades. In Gebel, H. G. K. & Kafafi, Z. (eds.), *The Prehistory of Jordan, II: Perspective from 1997.* Studies in Early Near Eastern Productions, Subsistence and Environment 4. Berlin.

Rosen, S. A. & Shugar, A. 2007. *Assays in understanding sickle gloss* (Poster). Austin Texas, April 27–May 1. Presented at the Meeting of the Society for American Archaeology.

Semenov, S. A. 1964. *Prehistoric technology: an experimental study of the oldest tools and artefacts from traces of manufacture and wear.* London.

Spurrell, F. C. J. 1892. Notes on early sickles. *Archaeological Journal* 49 (1).

Steensberg, A. 1943. *Ancient Harvesting Implements: Study in Archaeology and Human Geography.* Nationalmuseets skrifter, Arkæologisk-historisk række 1. Copenhagen.

Taipale, N. 2012. *Micro vs. Macro. A microwear analysis of quartz artefacts from two Finnish Late Mesolithic assemblages with comments on the earlier macrowear results, wear preservation and tool blank selection*. Master's thesis, Uppsala University.

Unger-Hamilton, R. 1983. An investigation into the variables affecting the development and the appearance of plant Polish on the blades. In Cauvin, J. (ed.), *Traces d'utilization sur les outils neolithiques du Proche Orient.* Travaux de la maison de l'Orient 5. Lyon

Unger-Hamilton, R. 1988. *Method in microwear analysis: prehistoric sickles and other stone tools from Arjoune, Syria.* British Archaeological Report, International Series 435. Oxford.

Unger-Hamilton, R. 1991. Natufian plant husbandry in the southern levant and comparison with that of the Neolithic periods: the lithic perspective. In Bar-Yosef, O. & Valla, F. (eds.), *The Natufian Culture in the Levant*. Michigan.

Vang Petersen, P. 1993. *Flint fra Danmarks oldtid*. København.

Vardi, J., Golan, A., Levy, D. & Gilead, I., 2010. Tracing sickle blade levels of wear and discard patterns: a new sickle gloss quantification method. *Journal of Archaeological Science* 37 (7).

Vaughan, P. 1985. *Use-wear analysis of flaked stone tools*. Tucson.

Witthoft, J. 1967. Glazed polish on flint tools. *American Antiquity* 32 (3).

Wyszomirski, M. 1979. Svenska depåfynd med s.k. lövknivar. *Fornvännen* 74.

Sebastian Boström, Kulturen, Lund, sebastian.bostrom@kulturen.com
Jon Lundin (corresponding author), independent researcher, Uppsala, lundin_jon@hotmail.com