The effect of worked material hardness on stone tool wear

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Abstract

The identification of ancient worked materials is one of the fundamental goals of lithic use wear analysis and one of the most important parts of understanding how stone tools were used in the past. Given the documented overlaps in wear patterns generated by different materials, it is imperative to understand how individual materials' mechanical properties might influence wear formation. Because isolating physical parameters and measuring their change is necessary for such an endeavor, controlled (rather than replicative) experiments combined with objective measurements of surface topography are necessary to better grasp how polish formed on stone tools. Therefore, we used a tribometer to wear natural flint surfaces against five materials (bone,

antler, beech wood, spruce wood, and ivory) under the same force, and speed, over one, three, and five hours. The study aimed to test if there is a correlation between polish formation and the hardness of the worked material. We measured each raw material's hardness using nano-indentation test, and we compared the surface texture of the polished flint bits using a 3D optical profilometer. The interfacial detritus powder was analyzed with a scanning electron microscope to look for abraded flint particles. We demonstrate that, contrary to expectation, softer materials, such as wood, create smoother polishes than hard ones, such as ivory.

Introduction

Along with the study of ancient residues, microscopic use wear analysis (MWA) is one of the two major and complementary methods of lithic traceology [1], the science of forensically interpreting ancient stone tool use. Despite its immense interpretive potential, its early spectacular results [e.g., 2] were tempered by the blind testing crisis of the 1980s [3,4], which put into question different researchers' ability to identify the same worked materials. Despite many advances since the 1980s [see 5–7,8 for reviews], the identification of different worked materials is still considered an insufficiently developed area. This is a major setback for prehistorians, because residues are not always preserved, and knowing which materials were worked can make an enormous difference in interpreting area or site function, or in claims about style and cultural transmission, etc.

The problem is manifold: not all polishes are equally easy to see and interpret, and not all types of data deliver the same answers. Some types of materials, such as cereals [9,10] or antler, bone, and ivory (ABI) have been identified consistently in blind tests or have been separated quantitatively in experimental settings with varying degrees of success (see [11–15]). Traces left

by others, especially by soft and elastic materials, such as meat, tendons, etc., are less identifiable [16]. Several quantitative studies did report success in distinguishing target materials, but, even here, within-group similarities were not adequately explained. For example, Stevens et al.'s [15] discriminant functions grouped antler with plant polishes. Moreover, some studies could not clearly distinguish wood [17] and hide polish [13] from unworked areas. In one of the most recent studies, Ibáñez et al. [12: 1188] report a similar overlap between some contact materials in their quantitative analysis as those noted by both other quantitative studies and also in blind tests [e.g., 18], despite studying one of the largest samples to date. Therefore, because the processes that lead to these differences and similarities in polish are not sufficiently well understood, we cannot understand why attempts to classify polishes produced by different materials fail or produce ambiguous results when they do.

One obvious way to resolve this problem is to study the mechanical properties of prehistoric target (worked) materials and test their effects on wear development. Unfortunately, these materials are not commonly studied by tribologists, as they have no industrial applications. They are also more variable than industrial ones, as the available data show. For example, the varying amount of mineralization in bone, ivory, and antler causes mechanical properties to also vary among species [19], in some cases significantly so [20]). Further, these materials change their properties when they are wet vs. dry [21], or in very cold weather conditions [particularly ivory, see 22]. While some have claimed that this produces different traces on stone tools, *why* that might happen remains insufficiently explained. Given that it is now widely believed that abrasion is the main process by which stone tools are polished during use [23–25], it makes sense to test first the effect of hardness. Until now, systematic mechanical tests of archaeologically-relevant target materials have not been incorporated into lithic use-wear research. In particular, hardness

tests were carried out on the stones themselves [26–29], but not on the target materials. For this reason, we decided to carry out a test of the target material hardnesses and to evaluate their role in abrading flint.

Method

Experimental setup

To isolate the effect of material hardness while maintaining reasonable costs and effort, we opted for a tightly controlled protocol [30,31]. Flint bits (Baltic/morainic flint from Denmark with nano-crystalline non-oriented chalcedony texture [25]) were rubbed against dry bone, antler, and wood (beechwood and spruce) using a tribometer at room temperature. Five samples of each pair were produced to obtain a suitable number of samples for statistical study. The experiment was sequential; the flint samples were mounted on the tribometer (Nanovea T-50) (Fig 1) and used sequentially for 1, 3, and 5 hours. The tribometer variables were fixed to a load of 20N, a speed of 35 revolutions per minute and a straight back and forth motion.

Fig. 1: **Tribometer setup.** A: overview; 1: Load(20N); 2: sample holder; 3: worked material (ivory). B: close-up; 3: worked material (ivory); 4: chert bit; 5: wear track.

Sample Preparation

Stone bits

The stone was first broken in small fragments using a hammer. The stone bits that had a flat natural surface on one side were selected. The opposite side was then adjusted to fit into the tribometer's clamp using a saw (Buehler, ISOMET TM, low speed saw) and then glued (Scotch Create Permanent Super Glue Liquid) to the clamp. The flat natural surface was rubbed against one of the worked materials selected. As polish develops unevenly on the sides of the sharp edge of a tool, this setup helps to create a sufficiently large polished area for carrying out microscopic analyses. The samples were cleaned before every documentation of wear. Because of the metallic nature of the clamp, a harsh cleaning protocol using acid and base was impossible and instead, a mild cleaning process was used. The samples were placed in individual plastic bags

filled with a 10% neutral soap solution (Valconox, Luminos). They were then immersed into an ultrasonic bath for 15 minutes (Branson 5800, 40 kHz, at room temperature, 22°C). Then they were rinsed with tap water and put in a distilled water bath for 5 minutes. Finally, samples were left to air-dry.

Hardness test

The hardness of each raw material was measured using a nano-indentation test. The samples were placed in resin using a SamplKwick Fast Cure Acrylic Kit 20-3560 (which contains SamplKwick Powder 20-3562 and SamplKwick Liquid 20-3564). The resin was prepared by a cold molding process done at room temperature by mixing two parts of 20-3562 SamplKwick Powder and one part of 20-3564 SamplKwick and blending thoroughly for 15-20 seconds. Then the mixture was poured into ring molds without delay. Before pouring the mix into the ring molds, we sprayed the cups with Mold release Spray (Buehler Mold Release Spray, 203050008). Finally, the surface of the cast was polished to obtain a smooth surface.

The nanoindentation measurements were performed using a nanoindenter (Fig 2) (TI 950, Triboindenter, Hysitron, Minneapolis, MN) equipped with a diamond Berkovitch indenter. Prior to the experiment, the tip area function and the frame stiffness were calibrated using a fused silica standard. Nanoindentation measurements were conducted using the Oliver-Pharr or the quasi-static loading mode [32–34] from which the reduced modulus (E_r) and hardness were estimated (Fig. 3) The initial unloading portion of the load-displacement curve represents purely elastic recovery. The slope of this unloading segment is a measure of the material contact stiffness [35]. The reduced Young's modulus (E_r) can be calculated by

$$E_r = \frac{1}{2} S \sqrt{\frac{\pi}{A_{max}}} \quad (1)$$

where S is the contact stiffness and A_{max} is the surface contact area at the maximum depth. The elastic modulus of the indented specimen, E_s is computed using

$$\frac{1}{E_r} = \frac{1-\nu_s^2}{E_s} + \frac{1-\nu_i^2}{E_i} \quad (2)$$

where ν_s is the Poisson's ratio of the indented specimen and E_i and ν_i are the Young's modulus and Poisson's ratio, respectively, of the indenter. For a diamond Berkovitch indenter, E_i is equal to 1141 GPa and ν_i is equal to 0.07 [36]. Since the Poisson's ratio of sedimentary rock ranges between 0.1 – 0.3, we have decided to report the E_r rather than estimate the E_s for modulus comparison (see S1 Appendix).

In addition, the hardness (H) can be calculated using the maximum load, P_{max} , by

$$H = P_{max}/A_c \quad (3)$$

where A_c is the contact area of the indentation. These quasi-static measurements were performed with a 5 s load time and a 10 s dwell time at a maximum load of 3000 μ N for stones and 300 μ N for, spruce wood, beech wood, bone, ivory, and antler (Table 1).

A

Fig. 2: Material reaction during the nanoindentation process. A: Schematic drawing showing the surface displacement during indentation; B: A typical indentation P - h curve where h_c is the maximum true contact displacement during loading, P_{max} refers to the maximum load applied during the indentation cycle, S is the initial unloading stiffness, h_f is the final plastic depth from the P - h curves, h_s is the residual depth after complete unloading and h_{max} is the indent.

Table 1: Raw materials average hardness and E_r values. These values are calculated taking all the measurements into account for each sample.

	Spruce wood	Beech wood	Bone	Antler	Ivory
Reduced Modulus	1.078 ± 0.359	$27.896 \pm$	$19.252 \pm$	$30.562 \pm$	$36.439 \pm$
(E_r in GPa)		11.062	1.128	5.128	0.323
Hardness	0.122 ± 0.004	2.685 ± 1.652	$2.936 \pm$	$3.253 \pm$	$3.930 \pm$
(H in GPa)			0.277	0.727	0.025

Analysis

An optical profilometer (S-Neox, Sensofar Metrology, Barcelona, Spain) was used to collect surface topography measurements before the experimentation and then at each step of the experiment. At each step, 3 to 5 measurements of different areas were taken for each sample. Measurements were acquired with both a 20× objective (TU Plan Fluor EPI P; NA = 0.45; FoV = $872.68\mu\text{m} \times 655.965\mu\text{m}$) and a 50× objective (TU Plan Fluor EPI P; NA = 0.80; FoV = $350.88\mu\text{m} \times 264.19\mu\text{m}$). Pictures were taken using the blue LED (530 nm) to obtain the highest resolution possible with our equipment. Only pictures with a surface measure higher than 98% were used for the analysis. The surface images were then analyzed using SensoMap (Standard 7.4). To extract surface parameters from the pictures, the filtering protocol presented in Calandra et al. [37] was used: (1) extraction of the topographic layer, (2) use of a Gaussian low-pass S-filter (S1 nesting index = $1.093\mu\text{m}$ for the 20× objective and $0.437\mu\text{m}$ for the 50×, end effects managed) to remove noise and keep the primary surface, (3) use of an F operator (polynomial of degree 3) to remove the form and keep the SF surface, i.e., texture, (4) use of a Gaussian high-pass L-filter (L nesting index = $327.980\mu\text{m}$ for the 20× objective and $131.200\mu\text{m}$ for the 50×, end effects managed) to filter out the waviness and keep the SL surface, i.e., roughness, and (5) setting threshold surface between 0.010 and 99.9% material ratio to remove the aberrant positive and negative spikes. It is important to note, however, that sometimes that threshold was readjusted depending on the persistence of the outliers. The cut-off values were calculated following ISO norms [38,39] recommendations; the L nesting index used was half the size of the shortest side (breadth) of the field of view, and the S1 nesting index was obtained by dividing the L nesting by 300 times. Four of the ISO25178 parameters were selected to perform the statistical analysis (Fig 3): arithmetic mean height (S_a), autocorrelation length (S_{al}), arithmetic mean peak

curvature (Spc), and the upper material ratio ($Smr1$). These four parameters, relatively independent, provide an overall understanding of the surface textures [40].

Fig. 3 Visual representation of the surface parameters. (from Martisius et al., 2018 (doi: <https://doi.org/10.1371/journal.pone.0206078.g004>)).

The statistical analyses were performed in the open-source software R (v. 3.5.2;[41] using the following packages: ggplot2 (v. 3.1.0; [42]), dplyr (v. 0.8.0.1; [43]), tidyr (v. 0.8.3; [44]), ggpubr (v. 0.1.2 ; [45]), ggalt (v. 0.4.0; [46]), MASS(v. 7.3-53.1; [47]), gridExtra (v.2.3; [48]), cowplot (v. 1.1.1; [49]) , rstatix(v. 0.7.0; [50]), and knitr (v. 1.31; [51]). Boxplots were produced to give a sense of the flint texture variation depending on the worked material hardness. Besides, an analysis of variance (ANOVA) and paired t-test were used to show which roughness parameters can help discriminate material types or hardness.

Results

180 **Direct observation results**

181 Visually, it is noticeable that polish did not develop to the same extent on all the flint bits, even
182 with the naked eye (Fig 4). According to the statistical results, the flint surface appears more
183 polished when rubbed on spruce wood and beech wood. For the other worked material, the
184 polish is sparser.

185

	Stone samples X30	Microtopography of the stone sample X50
Stone sample worked on Spruce wood
Stone sample worked on Beech wood
Stone sample worked on bone
Stone sample worked on antler
Stone sample worked on ivory

187 *Fig. 4 Polish development after 5 hours of use. The samples are organized by hardness order, from the softer on top of table to*
188 *the harder on the bottom.*

189

190 **Statistical results**

191 An analysis of variance (ANOVA) made on each parameter show that only the Sa ($p < 0.001$)
192 parameter is the only one that is statistically different (Fig 5). Hence, Sa is the most suited of the
193 four parameters tested to understand the worked material hardness's impact on polish formation.
194 The results indicate that the worked material modifies the natural flint surface quantitatively,
195 depending on its hardness. The softer a worked material is, the more the flint surface will be
196 polished.

Fig. 5 Boxplots showing the evolution of flint roughness parameters *Sa*, *Sal*, *Spc*, and *Smr1* after 1 hour, 3 hours and 5 hours of use on worked materials of various hardnesses. The diagrams in the first column represent the expected microtopography for a high value (on the top part of the cell) or low value (on the bottom part of the cell) for each parameter (extract from Martisius et al., 2018).

Paired t-tests with the Bonferroni correction results for the *Sa* parameter (see Table 2) show that it is possible to differentiate a flint piece before and after use only for the softest material, the

spruce wood ($p = 0.001$). It is also possible to differentiate between the two wood types ($p = 0.045$). However, for antler, ivory, and bone, the paired t-tests show that the means before and after use were not significantly different. In term of duration of the action, the results were statistically significant after 3 hours of use. However, the significance increased after 5 hours of user in particular to distinguish between the two wood types.

Table 2: paired t-test results with the Bonferroni correction and their significance. In the adjusted p-value significance column ns refers to non-significant, and the number of stars to the level of significance.

Parameter tested	worked materials		number of measurements		statistic	df	p	p-value adjusted using the Bonferroni correction	adjusted p-value significance
Sa	Antler	Beech wood	10	5	3.7703086	11.719557	3.00E-03	0.045	*
Sa	Antler	Bone	10	10	0.5388624	17.567535	5.97E-01	1	ns
Sa	Antler	Ivory	10	5	0.6032733	12.638991	5.57E-01	1	ns
Sa	Antler	Raw	10	40	1.4770012	10.563733	1.69E-01	1	ns
Sa	Antler	Spruce wood	10	5	10.74617	9.772127	1.00E-06	0.0000149	****
Sa	Beechwood	Bone	5	10	-3.5174487	10.386906	5.00E-03	0.075	ns
Sa	Beechwood	Ivory	5	5	-3.5850431	7.819647	7.00E-03	0.105	ns
Sa	Beechwood	Raw	5	40	-3.712811	4.82499	1.50E-02	0.225	ns
Sa	Beechwood	Spruce wood	5	5	6.176421	4.414617	3.00E-03	0.045	*
Sa	Bone	Ivory	10	5	0.0525376	11.680601	9.59E-01	1	ns
Sa	Bone	Raw	10	40	0.9199148	11.167691	3.77E-01	1	ns
Sa	Bone	Spruce wood	10	5	11.684085	10.044221	4.00E-07	0.0000054	****
Sa	Ivory	Raw	5	40	0.910415	5.136519	4.03E-01	1	ns
Sa	Ivory	Spruce wood	5	5	12.455777	4.561824	1.07E-04	0.001605	**
Sa	Raw	Spruce wood	40	5	26.334601	24.570355	0.00E+00	0	****

Track analysis

One reason that can explain these results could be the presence of more abrasive compounds in the softer worked material such as silicate. Residual powders from the track formed by the flint rubbing on the worked materials were collected and analyzed using scanning electron microscopy (SEM) and X-ray analysis (EDS) (Fig 6). Silica could not be found in the EDS framing the broad region of the samples, most likely because the other elements' noise was too heavy to enable the detection of other compounds or because the powdered silica are too small to be picked up by the EDS probe. However, we found that the interfacial powders from each raw material contained flint fragments of approximately 200µm.

Fig. 6: X-ray microanalysis of the spruce wood powder. The red square represents the scanned area. This area is mainly composed of Silicone, suggesting that the fragment (white on the picture) is a flint fragment.

In this case, the two softer materials happen to be wood, but silica content in temperate wood species is negligible [52], whereas the apatite contained in the bone matrix are softer than the quartz in flint. At the same time, because flint was found in track powders associated with all materials, it is possible that these particles contributed most to the abrasion, since they are hard enough to scratch the stone surface. However, we do not understand exactly how and why flint particles were broken off the stone surface in the first place. Although we tried to maintain a

contact between two relatively flat surfaces to maximize contact area and minimize the variation in pressure distribution, because we opted for a natural raw surface, edge breakages were still possible. Moreover, it is possible that the particles we found with the aid of the EDS probe are too large to have really contributed significantly to polish development.

Discussion

The basic problem in explaining what causes stone tool wear is that most worked materials (such as skins, wood, bone, etc.) are softer than stone and cannot, in theory, abrade the stone tools themselves. However, given that stone tools are, in fact, abraded by contact with softer materials [23–25], why does this happen, and which factors related to the target material play the most significant role? Our counterintuitive result suggests that the abrasion ‘paradox’ must be explained by either the presence of hard grits *within the worked material*, the presence at the interface *of stone particles broken off* the tool edge, or a combination of both [53]. In the second case, the ability of softer materials to cause stone particles to break off via a combination of friction heat and mechanical dislodging is likely determined by their own structure and mechanical properties. Therefore, knowing exactly to which degree these properties are responsible for creating wear is crucial for being able to recognize different worked materials.

The results obtained in this study confirm previous results stating that it is possible to differentiate between the softest material (woods) and harder ones (antler, bone, ivory) statistically. There also appears to be a statistical separation between the two types of wood, spruce and beech. However, using basic surface topography, it does not seem possible to distinguish among antler, bone, and ivory. These observations confirm previously reported

difficulties in visually differentiating polish within this group, which are often reported together as ABI [54,55].

An unresolved issue is that, even after 5 hours of work in our setup, the polish was barely developed on harder materials, while it was almost completely flat in the wood samples. Hence, for ivory, bone, and antler, it was impossible to distinguish the before and after use surfaces based on changes in *Sa*. In our previous work scraping beech wood [56], quantifiable differences in *Sa* were only documented with higher loads, of 90N and 100N. However, here we were able to obtain changes in *Sa* for the same material, beech wood, even with the comparatively much lower load of 20N. The discrepancy can be attributed to the difference in the ability of that paper's instrument (using focus variation) to measure polish and/or, given other teams' successes using focus variation [13], to the lack of a standardized surface on which to measure it. However, it is also possible that higher loads or much longer working durations are required to make noticeable changes to the stone surface. This could be due to processes involving dislodging particles from the stone surface using friction heat, which remain to be documented experimentally.

Conclusion

As discussed in another paper related to this experimental setup [25], polish is formed by abrasion of the flint surface. Consequently, we expect that harder worked material would be more effective in creating polish. However, our experiment shows that the softer the worked material is (i.e., the lower the arithmetical mean height (*Sa*)), the more the polish is developed. Given these results, it is imperative that other mechanical properties of materials typically expected to occur in prehistoric tasks be studied. These could include the materials' own surface

roughness, elasticity, fracture toughness, the presence and brittleness of embedded grits, and others. In addition, longer work duration and higher loads (with different machines) can be tested to obtain more polish formation on stone samples used on harder materials. Additionally, for this pilot study, materials were used in the dry condition, but saturation with water and added lubrication (e.g., fat) should be included in future studies.

Supporting information

S1 Appendix. Detailed results of the nano-indentation tests.

Bibliography

1. Fullagar R. Residues and usewear. In: Balme J, Paterson A, editors. *Archaeology in practice: a student guide to archaeological analyses*. Malden, Oxford, Carlton: Blackwell Publishing; 2006. pp. 207–234.
2. Keeley LH, Toth N. Microwear polishes on early stone tools from Koobi Fora, Kenya. *Nature*. 1981;293: 464–465. doi:10.1038/293464a0
3. Bamforth D. Investigating microwear polishes with blind tests: The Institute results in context. *J Archaeol Sci*. 1988;15: 11–23.
4. Newcomer MH, Grace R, Unger-Hamilton R. Investigating Microwear Polishes with Blind Tests. *J Archaeol Sci*. 1986;13: 203–217.
5. Grace R. Use-Wear Analysis: The State of the Art. *Archaeometry*. 1996;38: 209–229. doi:10.1111/j.1475-4754.1996.tb00771.x
6. Evans AA, Lerner H, Macdonald DA, Stemp WJ, Anderson PC. Standardization, calibration and innovation: a special issue on lithic microwear method. *J Archaeol Sci*. 2014;48: 1–4. doi:10.1016/j.jas.2014.03.002
7. Stemp WJ, Watson AS, Evans AA. Surface analysis of stone and bone tools. *Surf Topogr Metrol Prop*. 2015;4: 013001. doi:10.1088/2051-672X/4/1/013001
8. Macdonald DA, Stemp WJ, Evans AA. Exploring the microscale: Advances and novel applications of microscopy for archaeological materials. *J Archaeol Sci Rep*. 2018;18: 804–805. doi:10.1016/j.jasrep.2018.02.036

- 300 9. Ibañez JJ, González-Urquijo JE, Gibaja J. Discriminating wild vs domestic cereal harvesting
301 micropolish through laser confocal microscopy. *J Archaeol Sci.* 2014;48: 96–103.
302 doi:10.1016/j.jas.2013.10.012
- 303 10. Ibáñez JJ, Anderson PC, González-Urquijo J, Gibaja J. Cereal cultivation and domestication as shown
304 by microtexture analysis of sickle gloss through confocal microscopy. *J Archaeol Sci.* 2016;73: 62–
305 81. doi:10.1016/j.jas.2016.07.011
- 306 11. Evans AA, Donahue RE. Laser scanning confocal microscopy: a potential technique for the study of
307 lithic microwear. *J Archaeol Sci.* 2008;35: 2223–2230. doi:10.1016/j.jas.2008.02.006
- 308 12. Ibáñez JJ, Lazuen T, González-Urquijo J. Identifying Experimental Tool Use Through Confocal
309 Microscopy. *J Archaeol Method Theory.* 2019;26: 1176–1215. doi:10.1007/s10816-018-9408-9
- 310 13. Macdonald DA. The application of focus variation microscopy for lithic use-wear quantification. *J*
311 *Archaeol Sci.* 2014;48: 26–33. doi:10.1016/j.jas.2013.10.003
- 312 14. Pedergrana A, Calandra I, Evans AA, Bob K, Hildebrandt A, Ollé A. Polish is quantitatively different
313 on quartzite flakes used on different worked materials. Peresani M, editor. *PLOS ONE.* 2020;15:
314 e0243295. doi:10.1371/journal.pone.0243295
- 315 15. Stevens NE, Harro DR, Hicklin A. Practical quantitative lithic use-wear analysis using multiple
316 classifiers. *J Archaeol Sci.* 2010;37: 2671–2678. doi:10.1016/j.jas.2010.06.004
- 317 16. Unrath G, Owen LR, van Gijn A, Moss EH, Plisson H, Vaughan P. An Evaluation of Use-Wear Studies:
318 a Multi-Analyst Approach in Technical Aspects of Microwear Studies on Stone Tools. *Early Man*
319 *News.* 1984; 117–176.
- 320 17. Stemp WJ, Stemp M. Documenting Stages of Polish Development on Experimental Stone Tools:
321 Surface Characterization by Fractal Geometry Using UBM Laser Profilometry. *J Archaeol Sci.*
322 2003;30: 287–296. doi:10.1006/jasc.2002.0837
- 323 18. Evans AA. On the importance of blind testing in archaeological science: the example from lithic
324 functional studies. *J Archaeol Sci.* 2014;48: 5–14. doi:10.1016/j.jas.2013.10.026
- 325 19. Pfeifer SJ, Hartrampf WL, Kahlke R-D, Müller FA. Mammoth ivory was the most suitable osseous
326 raw material for the production of Late Pleistocene big game projectile points. *Sci Rep.* 2019;9:
327 2303. doi:10.1038/s41598-019-38779-1
- 328 20. Chen P-Y, Stokes AG, McKittrick J. Comparison of the structure and mechanical properties of
329 bovine femur bone and antler of the North American elk (*Cervus elaphus canadensis*). *Acta*
330 *Biomater.* 2009;5: 693–706. doi:10.1016/j.actbio.2008.09.011
- 331 21. Currey JD, Landete-Castillejos T, Estevez J, Ceacero F, Olguin A, Garcia A, et al. The mechanical
332 properties of red deer antler bone when used in fighting. *J Exp Biol.* 2009;212: 3985–3993.
333 doi:10.1242/jeb.032292
- 334 22. Khlopachev GA, Giryay EY. Sekrety drevnikh kostorezov Vostochnoy Evropy i Sibiri: priemy obrabotki
335 bivnya mamonta i roga severnogo olenya v kamennom veke [Secrets of ancient carvers of Eastern

- Europe and Siberia: treatment ivory and reindeer antler in the Stone Age]. Saint Petersburg: St Petersburg publishing house "Nauka"; 2010.
23. Yamada S. The formation process of use-wear polishes. *Traces Fonct Gestes Retrouvés*. 1993;50: 2.
 24. Ollé A, Vergès JM. SEM functional analysis and the mechanism of microwear formation. In: Longo L, Skakun N, editors. "Prehistoric Technology" 40 years later: functional studies and the Russian legacy. Oxford: Archaeopress; 2008. pp. 39–49.
 25. Schmidt P, Rodriguez A, Yanamandra K, Behera RK, Iovita R. The mineralogy and structure of use-wear polish on chert. *Sci Rep*. 2020;10: 21512. doi:10.1038/s41598-020-78490-0
 26. Astruc L, Vargiolu R, Zahouani H. Wear assessments of prehistoric instruments. *Wear*. 2003;255: 341–347. doi:10.1016/S0043-1648(03)00173-X
 27. Lerner H, Du X, Costopoulos A, Ostoj-Starzewski M. Lithic raw material physical properties and use-wear accrual. *J Archaeol Sci*. 2007;34: 711–722. doi:10.1016/j.jas.2006.07.009
 28. Lerner HJ. 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. *J Archaeol Sci*. 2014;48: 34–45. doi:10.1016/j.jas.2013.10.030
 29. Yonekura K, Hotta A, Suzuki T. Influence of intrinsic properties of prehistoric stone tool materials on development of use-wear traces. *Quat Res Daiyonki-Kenkyu*. 2011;50: 195–204. doi:10.4116/jaqua.50.195
 30. Marreiros J, Pereira T, Iovita R. Controlled experiments in lithic technology and function. *Archaeol Anthropol Sci*. 2020;12: 110, s12520-020-01059–5. doi:10.1007/s12520-020-01059-5
 31. Marreiros J, Calandra I, Gneisinger W, Paixão E, Pedergnana A, Schunk L. Rethinking Use-Wear Analysis and Experimentation as Applied to the Study of Past Hominin Tool Use. *J Paleolit Archaeol*. 2020;3: 475–502. doi:10.1007/s41982-020-00058-1
 32. Hay J, Agee P, Herbert E. Continuous stiffness measurement during instrumented indentation testing. *Exp Tech*. 2010;34: 86–94. doi:10.1111/j.1747-1567.2010.00618.x
 33. Li Y, An B, Fukuyama S, Yokogawa K, Yoshimura M. Surface oxidation of a Nb(100) single crystal by scanning tunneling microscopy. *Mater Charact*. 2002;48: 163–167. doi:10.1016/S1044-5803(02)00204-8
 34. Oliver WC, Pharr GM. An improved technique for determining hardness and elastic modulus using load and displacement sensing indentation experiments. *J Mater Res*. 1992;7: 1564–1583. doi:10.1557/JMR.1992.1564
 35. Oyen ML, Cook RF. A practical guide for analysis of nanoindentation data. *J Mech Behav Biomed Mater*. 2009;2: 396–407. doi:10.1016/j.jmbbm.2008.10.002

- 369 36. Oliver WC, Pharr GM. Measurement of hardness and elastic modulus by instrumented indentation:
370 Advances in understanding and refinements to methodology. *J Mater Res.* 2004;19: 3–20.
371 doi:10.1557/jmr.2004.19.1.3
- 372 37. Calandra I, Schunk L, Rodriguez A, Gneisinger W, Pedernana A, Paixao E, et al. Back to the edge:
373 relative coordinate system for use-wear analysis. *Archaeol Anthropol Sci.* 2019 [cited 21 Feb 2019].
374 doi:10.1007/s12520-019-00801-y
- 375 38. Organization for Standardization. 4288—Geometrical product specifications (GPS)—surface
376 texture: profile method—rules and procedures for the assessment of surface texture. 1996.
- 377 39. Organization for Standardization. 4287—Geometrical Product Specifications (GPS)—Surface Texture:
378 Profile Method—Terms, Definitions and Surface Texture Parameters. International. 1997.
- 379 40. Martisius NL, Sidéra I, Grote MN, Steele TE, McPherron SP, Schulz-Kornas E. Time wears on:
380 Assessing how bone wears using 3D surface texture analysis. *PLOS ONE.* 2018;13: e0206078.
381 doi:10.1371/journal.pone.0206078
- 382 41. R Core Team. R. A language and environment for statistical computing. R Foundation for Statistical
383 Computing, Vienna, Austria. Version 3.5.1. 2018. Available: <https://www.R-project.org/>
- 384 42. Wickham H. *ggplot2: Elegant Graphics for Data Analysis.* Springer; 2016.
- 385 43. Wickham H. Version 0.8.0.1, A Grammar of Data Manipulation. 2019. Available: [https://cran.r-](https://cran.r-project.org/web/packages/R.utils/R.utils.pdf)
386 [project.org/web/packages/R.utils/R.utils.pdf](https://cran.r-project.org/web/packages/R.utils/R.utils.pdf)
- 387 44. Wickham H. *tidyr*, Version 0.8.3, Easily Tidy Data with “spread()” and “gather()” Functions. 2019.
388 Available: <https://mran.revolutionanalytics.com/web/packages/tidyr/tidyr.pdf>
- 389 45. Kassambara A, Kassambara MA. Package ‘ggpubr.’ 2020.
- 390 46. Rudis B, Rudis MB. Package ‘ggalt.’ 2016.
- 391 47. Ripley B, Venables B, Bates DM, ca 1998) KH (partial port, ca 1998) AG (partial port, Firth D. MASS:
392 Support Functions and Datasets for Venables and Ripley’s MASS. 2021. Available: [https://CRAN.R-](https://CRAN.R-project.org/package=MASS)
393 [project.org/package=MASS](https://CRAN.R-project.org/package=MASS)
- 394 48. Auguie B, Antonov A. *gridExtra: Miscellaneous Functions for “Grid” Graphics.* 2017. Available:
395 <https://CRAN.R-project.org/package=gridExtra>
- 396 49. Wilke CO. *Cowplot, Streamlined Plot Theme and Plot Annotations for “ggplot2”,* Version 0.9.4.
397 2019. Available: <https://cran.r-project.org/web/packages/cowplot/cowplot.pdf>
- 398 50. Kassambara A. *rstatix: Pipe-Friendly Framework for Basic Statistical Tests.* 2021. Available:
399 <https://CRAN.R-project.org/package=rstatix>
- 400 51. Xie [aut Y, cre, Vogt A, Andrew A, Zvoleff A, <http://www.andre-simon.de>] AS (the C files under
401 inst/themes/ were derived from the H package, et al. *knitr: A General-Purpose Package for*
402 *Dynamic Report Generation in R.* 2021. Available: <https://CRAN.R-project.org/package=knitr>

- 403 52. Fullagar RLK. The role of silica in polish formation. *J Archaeol Sci.* 1991;18: 1–24.
404 doi:10.1016/0305-4403(91)90076-2
- 405 53. Stachowiak GW, Batchelor AW. *Engineering tribology*. Fourth edition. Oxford:
406 Elsevier/Butterworth-Heinemann; 2014.
- 407 54. Sano K. Functional variability in the Magdalenian of north-western Europe: A lithic microwear
408 analysis of the Gönnersdorf K-II assemblage. *Quat Int.* 2012;272–273: 264–274.
409 doi:10.1016/j.quaint.2012.02.057
- 410 55. Iwase A. A functional analysis of the LGM microblade assemblage in Hokkaido, northern Japan: A
411 case study of Kashiwadai 1. *Quat Int.* 2016;425: 140–157. doi:10.1016/j.quaint.2016.04.008
- 412 56. Pfleging J, Iovita R, Buchli J. Influence of force and duration on stone tool wear: results from
413 experiments with a force-controlled robot. *Archaeol Anthropol Sci.* 2018 [cited 9 Apr 2019].
414 doi:10.1007/s12520-018-0729-0
- 415