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Dents in our confidence: The interaction of damage and material properties in interpreting use-wear on copper-alloy weaponry

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ABSTRACT

The presence or absence of use-wear marks on copper (Cu)-alloy weaponry has been used since the late 1990s to investigate the balance between functional (combat) and symbolic (value, status, religious) use of these objects, and thus explore their social and economic context. In this paper, we suggest that this work has not taken sufficient account of the material properties of Cu-alloys. We discuss mechanisms of plastic deformation, incremental repairs and corrosion in detail to show how these can obscure use-wear traces. In a survey of Cu-alloy weaponry from the Nordic Bronze Age (1800/1700–550 BCE) from Denmark, Sweden and Germany, we show that corrosion of Cu-alloy objects is strongly linked to depositional context, being greater in burials (both inhumations and cremations) than hoards or as single objects. A relative paucity of use-wear marks on burial weapons should therefore not be used to argue that these were purely symbolic objects, e.g. in contrast to the better preserved hoard material. We propose that use-wear traces on Cu-alloy weaponry, particularly on blade edges, is significantly more elusive than previously realised, and that undamaged objects have been over-identified.

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1. Introduction

The first use-wear studies on metal weaponry pre-date the surge in the study of warfare of the past 20 years (Carman, 1997; Carman and Harding, 1999; Keeley, 1996; Molloy, 2007a; Otto et al., 2006; Uckelmann and Mödlinger, 2011). Two studies stand out as the earliest that reconstruct fighting styles and social organization by means of analysing the use-wear on copper (Cu)-alloy weaponry in particular. Schauer (1979) reconstructed a fencing fighting style for Late Bronze Age spears based on the notches on the blade of a spear discovered in a grave in Gau Algesheim, Germany. In his seminal analysis of period II and III swords, Kristiansen (1979, 1984; see also Kristiansen, 2002) used the stages of reduction of shape through use and repair to argue for a division of Nordic Bronze Age society into classes of fighters, who used swords as tools (objects often damaged and repaired), and an elite, who used swords as status signifiers (objects show no damage). However interesting the interpretations, neither study considered the material properties of Cu or the working and effects of corrosion on the shape of the weapon when recovered. Even in recent publications, such considerations are not factored into interpretations. For example, in an otherwise excellent study of the spearhead from Hochgosch, Austria, the corrosion of the entire blade edge is noted (Mödlinger, 2011a: 13). Despite this, the spear is still interpreted as a throwing and thrusting implement, precisely because of the lack of damage to the edge (contra Anderson, 2011):

> *"Wird der Speer als Wurfspeer oder Stoßwaffe eingesetzt, wird die Schneide kaum, die Spitze dagegen umso mehr beschädigt. Tatsächlich weisen Speerspitzen häufig Beschädigungen oder Abnutzungsspuren an der Spitze – wie auch die vorliegende Speerspitze! – und nur selten an der Schneide auf" [If the spears were used as throwing or thrusting implements, then their edges will only rarely be damaged but their tips will be more frequently damaged. Spearheads do indeed frequently show damage or use-wear on their tips – as does the discussed spearhead! – and only rarely on their cutting edges]* Mödlinger, 2011a*: 17).*

Such source-critical considerations are all the more important as use-wear studies attempt to join the ranks of the established archaeological sciences (Dolfini and Crellin, 2016). In order to delineate what can be said about the use of a given object or group

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of artefacts, it is necessary to know what cannot be known. A large variety of use-wear can be found on Cu-alloy weaponry (Dolfini and Crellin, 2016; Horn, 2013a, 2013b, 2014a,b; O'Flaherty et al., 2008; Gutiérrez Sáez and Martín Lerma, 2015; Uckelmann, 2012). We argue here that interpretations of Cu-alloy weaponry have frequently lacked a consideration of the material properties of Cu (but see Soriano Llopis and Gutiérrez Sáez, 2009), specifically (1) the mechanics of impact, (2) effects of repair processes and (3) effects of the chemistry of Cu corrosion. We discuss three major mechanisms of damage to Cu-alloy weaponry, and show how consideration of the material properties of Cu can alter previous interpretations of these types of damage. Corrosion and patina formation are explored in greatest detail, because the formation of wear and repair processes have been well-addressed elsewhere (see references in section 2).

2. Mechanism 1: consequences of plastic deformation

A variety of wear marks have been defined, such as notches, nicks, indentations, curvatures, and fractures (swords: Bridgford, 1997, 2000; Bunnefeld and Schwenzer, 2011; Colquhoun, 2011; Horn, 2013a, 2014a; Kristiansen, 1979, 1984, 2002; Matthews, 2011; Molloy, 2011; Quilliec, 2008; York, 2002; spears: Anderson, 2011; Horn, 2013a, 2013b, 2014a; Schauer, 1979; daggers: Dolfini, 2011; York, 2002; halberds: Brandherm, 2011; Dolfini, 2011; Horn, 2013a; 2013b, 2014b; O'Flaherty, 2002; other weapons: Gutiérrez Sáez et al., 2014; for more see the edited volume by Uckelmann and Mödlinger, 2011). Interpreting these traces as combat marks hinges on the integration of information from the archaeological record, experimental testing of metal behaviour, and a comparison between wear produced experimentally and wear observed on the archaeological material (Dolfini and Crellin, 2016).

The basic reactive mechanics of the metal to impacts have been explored in the material sciences (Lemaître, 1996). However, these experiments typically employ homogenous metals and alloys, in a relatively small range of shapes, responding to a relatively small range of possible impact types. These studies allow us to make predictions about the force of an impact and the general form of the impacting surface. However, the data are not necessarily straightforwardly applicable to the irregularity of archaeological objects, where casting flaws may be present, and where alloy composition and grain size may vary throughout the object. Here, experimental approaches have been and continue to be invaluable in distinguishing between different impacting objects.

Different wear marks indicate different uses, because they are caused by differently shaped objects, with different material properties, impacting each other at a range of velocities (experimental observations from Anderson, 2011; Gutiérrez Sáez and Martín Lerma, 2015; Molloy, 2007b, 2008, 2009; O'Flaherty, 2007; O'Flaherty et al., 2008; O'Flaherty et al., 2011). Thus, the presence of a V-shaped notch in a blade (Anderson, 2011; Bridgford, 1997, 2000; Horn, 2013a,b; O'Flaherty et al., 2008, Fig. 1a–b) is generally considered the best indicator of the use of a weapon in combat, because it was most likely caused by the impact of another cutting edge (Horn, 2013a,b; Gutiérrez Sáez and Martín Lerma, 2015). Other potential marks of combat are indentations, U-shaped wear marks on the cutting edge of a weapon, which may have been caused by an impact of a rounded surface such as the handle of another weapon or a bone. Deformation of a weapon's tip may be caused by impacting a surface approximately perpendicular to its longitudinal axis. Thus, the nature of use wear on weapons may be used to reconstruct object use or fighting style.

In this discussion we focus on the interaction of weapon material properties with use wear damage, without reference to how these may be interpreted to reconstruct object use or fighting style. We focus on the V-shaped notch as an example, because (1) the origin of these features is relatively specific (cutting edge to cutting edge contact), and (2) this single type of impact can lead a variety of material consequences.

In keeping with material sciences handbooks, we use the following definitions for material properties to discuss this issue further (Callister and Rethwisch, 2010; Hall, 1970; Hornbogen, 1975; Hussein et al., 2006; Rattan, 2008; Wei, 2010):

- *Plasticity*: the ability to relieve forces by plastic deformation before a material breaks. *Ductility* is the ability to deform under tensile stress and *malleability* is the ability to deform under compressive stress. The opposite property to plasticity is *brittleness*. Brittle materials will not deform under stress, but fracture quickly.
- *Hardness*: the mechanical resistance against mechanical penetration, including scratching and surface abrasion. Standard tests for hardness measure the effects of a perpendicular force applied to flat surface (e.g. Lawn and Howes, 1981).
- *Fracture*: the separations of an object into two or more pieces. These are of two types, with plastic deformation (ductile fractures) and without plastic deformation (brittle fractures; Campbell (2008: 222–224). A ductile-to-brittle transition exists. Campbell (2008: 223) names as specific example of a ductile fracture that can promote brittle fracture: "*Deep notches that create constraint at the crack tip*". For copper alloys, *stress cracking* induced by corrosion is another form of brittle fracture (see section 4).
- *Ultimate strength*: the maximal load a material can withstand before it fractures. The strength results from the *load* (*stress*) divided by the area it affects.
- *Toughness*: depends on a material's capability to absorb energy per unit volume including plastic deformation without fracture. Toughness depends on the material's plasticity and ultimate strength. *Notch-toughness* has been introduced (Lambrinou, 2011: 32–34) to account for a material's toughness in the presence of flaws such as notches or cracks.
- *Yield point*: is the point at which a material cannot recover plastic deformation (*strain*) under a load. This happens after the *stress-strain relation* exceeds the *elastic limit.*

The force required to form a notch is defined by the relative hardness, toughness and ultimate strength of both impacting objects (compare Soriano Llopis and Gutiérrez Sáez, 2009). However, standard definitions of these quantities cannot easily be applied to understanding use wear damage to archaeological objects. Edge hardening is observed on many Cu and bronze weapons in Europe so that we can assume that hardness was a desired property for example for cutting edges (Penniman and Allen, 1960; Faoláin and Northover, 1998; Valério et al., 2014). Hardness therefore varies within archaeological weapons because of variation in metal composition; however hardness also depends on the morphological complexity of the objects (e.g. proximity to an edge) and the angle of impact of the penetrating object. Toughness and ultimate strength, which are decisive in determining whether plastic deformation or fracture occurs, are defined relative to the load and the area over which the load is applied: they therefore also strongly depend on object morphology. Notch formation is therefore a complex, relational process, depending on the morphology and material properties of the objects involved.

Impacts which lead to notch formation may further lead to a range of other features of damage, which are systematically related to the relative material properties and morphologies of the penetrating and penetrated objects. At the moment of impact, material in the penetrated object is replaced with the material of the

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