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ORIGINAL ARTICLE

‘The sword that was broken …’: The detection of recycled iron in the archaeological record

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Abstract

Although the recycling of materials such as copper and glass is widely known and generally well understood within archaeological contexts, far less is known about the recycling of iron. Iron recycling is more complex than that of other metals for two reasons. First, normal manufacturing processes, which include forging several components to make a composite object, offer the opportunity to include recycled iron. Second, the material itself is more complex than Cu alloys. The alloys of Fe, depending primarily on C content, are very different in terms of properties and can be interconverted by (normally) removing C such as decarburizing cast iron to make wrought iron. Thus, recycling practices are potentially intimately combined with such processes. These factors, combined with the poor preservation of archaeological iron and the consequent reluctance to carry out extensive studies (which often require destructive analysis via metallography), mean that there are no clear criteria for identifying recycled iron. However, limited historical documentation suggests, at least indirectly, that such recycling was common. This paper is neither comprehensive nor definitive, but merely intends to promote discussion and awareness of iron recycling by hypothesizing several possible mechanisms and providing a few illustrative archaeological examples.

KEYWORDS

alloying, iron, materials studies, metal recycling, metallography

INTRODUCTION

The recycling of materials is now an essential process in much of the modern world. The rationale for this is widely recognized as 'benefitting the planet': reducing waste, reducing the demand for raw materials, reducing the cost of new products. It is increasingly clear that recycling has also played a significant role in the ancient world, but probably for a wider range of motives—certainly including economic considerations, but potentially also encompassing a wide range of symbolic and cultural reasons (Sainsbury et al., 2021). Thus, there has been a growing volume of literature on recycling in the archaeological record, focusing largely on glass (Bidegaray & Pollard, 2018; Degryse et al., 2006; Degryse & Shortland, 2020; Foster & Jackson, 2010; Freestone, 2015; Sainsbury, 2018, 2019; Silvestri, 2008; Silvestri et al., 2008) and Cu alloys (Baumeister, 2004; Bray & Pollard, 2012; Mödlinger & Trebsche, 2021; Pollard et al., 2015, 2018).

Although the recycling of metals other than copper is generally assumed to have taken place in the pre-modern era, the archaeological literature is, however, surprisingly silent about it. Both gold and silver must have been heavily recycled throughout history, and yet few publications have addressed this. With a few exceptions (e.g., Fleming, 2012; Park et al., 2019, 2020; Schwab, 2002; Schwab et al., 2006; Stepanov et al., 2019), iron is also generally excluded from this debate, and yet there is enough historical evidence to suggest that iron was indeed recycled in both antiquity and the early modern period. This represents a gap in our knowledge, since iron featured heavily in later prehistoric life, but is poorly represented within materials studies of archaeological metals, largely because of the generally poor preservation of iron artefacts. Consequently, there are no universally agreed physical or chemical markers for the recycling of iron. This apparent low level of interest is also reflected in the general difficulties of provenancing iron (Charlton, 2015), given that success in provenancing and the degree of recycling tend to be inversely correlated.

This paper discusses some of the possible ways in which iron may have been recycled in the past—it is neither a conclusive nor a comprehensive discussion. It is merely intended to stimulate further consideration of the possibilities and encourage others to look for evidence. Some examples of recycled iron objects are presented—again, this is neither a comprehensive nor exhaustive set of samples, but simply some illustrations of what can be found.

Iron can be smelted in two distinctive ways: the solid-state (direct) bloomery process and the (later) liquid cast-iron (indirect) process. This is to be contrasted with most other metals that have only one smelting method (Baumeister, 2004; Schubert, 1957). In the solid-state process, the bloom has to be worked to produce useable iron. Subsequent processing (forging and welding) is necessary to produce tools and weapons, and it is common to produce composite objects by welding together different grades of iron (including steel). This is sometimes followed by complex working practices to produce visual effects such as pattern welding. At most of these stages, there is the possibility of introducing older pieces of iron and steel, indicating the need for the discussion of recycling.

HISTORICAL REFERENCES TO, AND ARCHAEOLOGICAL EVIDENCE FOR, IRON RECYCLING

Iron reuse (scrap or recycled) is likely to have been a major part of the iron industry from the Iron Age onwards, although little physical evidence has been presented to show that this was the case. Additionally, it is clear that, compared with Cu alloys, references to the recycling of iron are much less abundant in the historical record. A clear example of this record for copper is a surviving detailed contemporary recipe for the casting of a Cu alloy bell in Bridgwater, Somerset (UK), in 1284 CE, which shows that at least 33% of the melt (which weighed 1781 lb, or over 800 kg) was recycled metal (Pollard, 2023: 953).

Much of the evidence for the recycling of iron in England is indirect and comes from post-medieval documents, in which economic historians have identified that 'old iron' was a common component in the inventories of blacksmith's workshops (Woodward, 1985: 183–186). Furthermore, late 17th- and early 18th-century probate inventories report that four out of eight blacksmiths in Kent held stocks of 'old iron', and, more specifically, '[o]ut of 39 inventories for Lincolnshire blacksmiths during the years 1550 to 1590, eight refer to unspecified iron in stock, four list new and old iron, one lists new iron only, and one gives old iron only' (185). Woodward concludes that '[a]lthough probate inventories do not always specifically list "old iron", it is inconceivable that blacksmiths would not have re-used materials when the opportunity arose—as they still do today' (p, 185).

Evidence for the recycling of iron also takes the form of documentary evidence for the trade in scrap iron, even on an international scale. Perhaps surprisingly, given the widespread distribution and manufacture of iron, England was a major importer of iron from at least the 13th century CE, mostly from Spain. In the 16th century, a *Tudor Book of Rates* reported that the cost of old iron was 5 shillings per hundredweight (50 kg), except for Spanish iron, which was rated at 1 shilling less per hundredweight (Willan, 1962: 35). A sequence of port records from the mid-15th and 16th centuries shows that old iron from the Basque Country was traded as bars (referred to as *endys*) through Bristol (Childs, 1981; Crew et al., 1997). This continued through the 17th and 18th centuries with records showing that 'old iron' was traded through Bristol, Hull, London and Yarmouth, often in parallel to a trade in new iron (Woodward, 1985: 186).

Clearly in the pre-modern era in Europe, scrap iron was an important component of the metal trade, and this could only be for recycling. The scale of such a trade is difficult to estimate, but one suggestion is that 'it is highly likely that the recycled iron comprised considerably more than ten per cent of a blacksmith's raw materials, especially in areas at some distance from ports or from areas of primary production' (Woodward, 1985: 186). These references focus on bloomery iron, and essentially on secondary ironworking—the work of the blacksmith. An interesting and different perspective comes from a 19th-century account in China, which describes the work of a 'tinker' repairing a cracked cast-iron wok by casting on molten iron from a small portable furnace—such a repair is presumably effected using scrap iron, thereby extending the life of the wok (Balestier, 1851). This is not unlike the more developed 'thermite' process still used to join sections of continuous railway track.

Occasionally, a reused or refashioned iron artefact can be found that matches a description from a contemporary written source. In the tenth century CE, the Icelandic *Gisla Saga* reports that the spear *Graisida* (grey sides) is said to have been made from a broken pattern-welded sword of the same name: 'Now the broken *Graisida* was taken, and Thorgrum made a spear from it, and it was ready by evening. There were patterns [*mal*] on it' (Ellis Davidson, 1994: 127). The same spear is later referred to in the *Sturlunga Saga* (iv, 26; vi, 17) as a *malaspjotr* or patterned spear, and it appears that it was still in use at the Battle of Orlygstadt (21 August 1238), about 270 years later:

> Sturla defended himself with the spear called *Graisida* nimbly and well: it was a great *malaspjotr* [pattern-welded spear], old and apt to bend. He thrust so vigorously with this that men fell before him continually; but the spear bent and he straightened it out under his feet several times. (127)

The spearhead *Graisida* seems to have been fashioned from a fragment of broken and possibly old sword blade sometime in the tenth century. Very few examples of sword blade fragments refashioned into spearheads have so far been found (or recognized), although one very good, near contemporary, example was found in the River Thames at Standlake, Oxfordshire (Ashmolean Museum, 1949-960). It had previously been electrolytically stripped of any corrosion products leaving a clearly visible pattern-welded structure (Figure 1). It has the distinctive appearance of a reworked sword fragment that is much thinner for its general size than contemporary purpose-made spears.

Probably the largest single assemblage of archaeological iron yet discovered is that from the Assyrian palace of Sargon II (r. *c.*722–705 BCE) at Khorsabad (Dur-Sharrukin), 15 km northeast of Mosul in northern Iraq. When excavated, it was found to have a storeroom ('magasin des fers', Room 86) containing 160 t of iron, much of which was in the form of iron bars—identifiable as trade iron—many of which were in the shape of fishes (Figure 2). The pointed end and thin, flat 'fishes tail' of these bars are both likely to be markers of the quality of the iron and how it could be drawn out, without cracking, during forging. There were also finished artefacts such as picks and chains, which may have been intended for recycling. We may assume that from the location in the palace and the form of the objects, the material in such a store was destined for forging into objects, probably weapons. The assemblage is generally assumed to have been acquired through tribute and plunder (Hertz, 1925; Place, 1867: 84–89; Pleiner & Bjorkman, 1974: 293), thus providing indirect evidence for recycling, although this would require further extensive analysis to be sure.

Such large archaeological assemblages of iron objects are rare. Smaller hoards are often found, with variously so-called 'currency bars', 'trade bars' or 'semi-products'—all of which may be classed as 'trade iron' – which may be taken as indicators of regional or larger trading networks in iron (Allen, 1967; Berranger & Fluzin, 2012; Crew, 1994; Fox, 1940). These objects take many forms, but are thought to be partially refined bloomery iron specifically shaped into recognizable forms for trade purposes. The Khorsabad bars fit with this explanation, as do many 'currency bars' found in later Iron Age European contexts (Crew, 1994, 1995). Occasionally, such objects are found on board shipwrecks, confirming their status as items of trade (Birch & Martinón-Torres, 2014; Crew et al., 1997; Galili et al., 2015). They do not, of course, provide evidence either way in terms of the ubiquity of iron recycling, since they could be either fresh products from the bloomery, iron reforged into bars for trade or some combination of the two.

IRON PRODUCTION AND THE FORMS OF IRON RECYCLING

The nature of iron recycling is intimately connected with the different processes of manufacturing iron. Unlike copper, which is workable in its native form and relatively easily smelted, iron

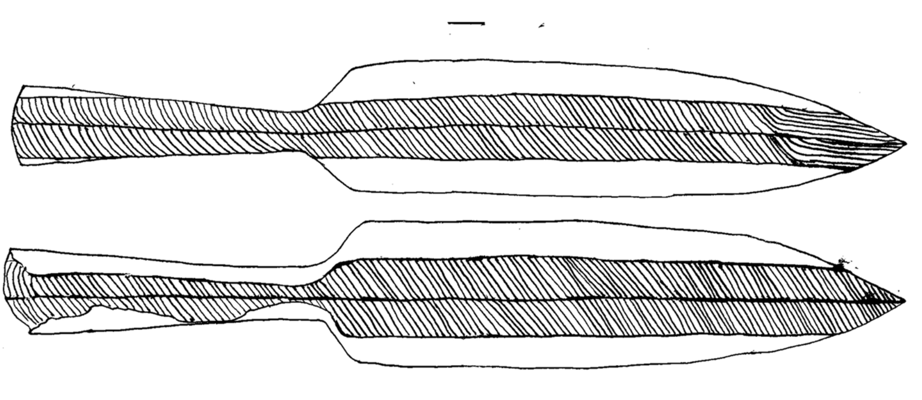

FIGURE 1 Standlake Late Anglo-Saxon spearhead (Ashmolean Museum, Oxford, 1949-960) made from an earlier sword fragment

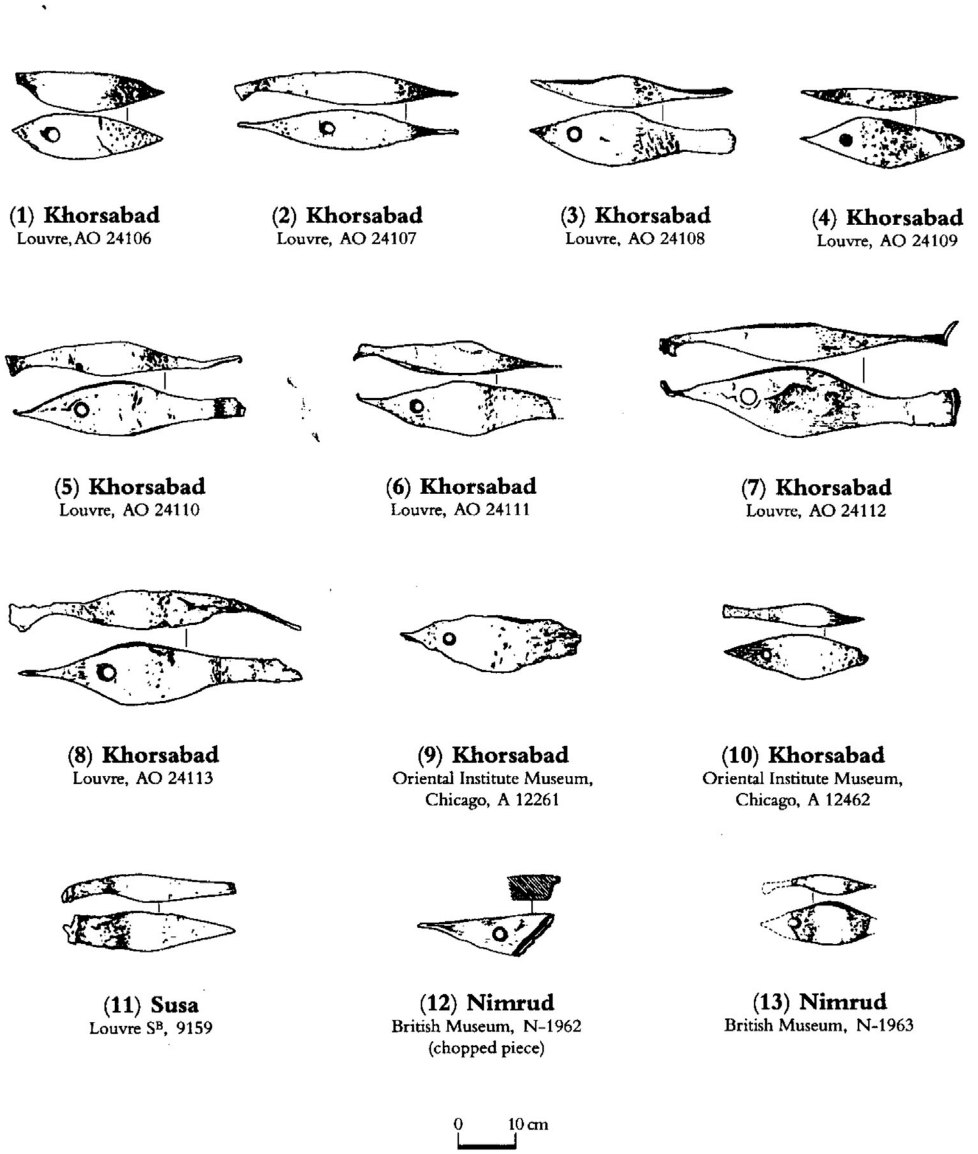

FIGURE 2 Khorsabad fish-shaped iron bars (Hoyland & Gilmour, 2006: fig. 17)

has a much higher melting point of 1535°C and therefore in pre-modern times was smelted in the solid state as 'bloomery' iron (Pleiner, 2006). Bloomery iron was the only form of extractive iron metallurgy practised in Europe until the late Middle Ages. Smelting iron in a bloomery furnace requires a large quantity of charcoal as fuel/heat source and to provide the reducing agent necessary to produce metallic iron from its ore. In addition to the iron ore and charcoal, bellows are used to pump air into the furnace to raise the temperature high enough both to reduce Fe oxide to metallic iron and to separate the spongy mass of iron produced this way (the bloom) from the stony waste of the ore as semi-liquid 'slag'. This happens at about 1200°C, well below the melting point of iron (Pleiner, 2006). This is a one-stage or 'direct' solid-state reduction process, in which the iron never becomes molten and is removed from the furnace as a still hot, semi-solid 'bloom'[1] (a spongy, heterogeneous pasty mass of iron and slag containing various non-metallic impurities), which requires subsequent forging while still hot to remove most of the remaining entrapped slag (Pleiner, 2006). Due to bloomery smelting conditions, iron smelted in this way may be expected to contain a few accidental minor or trace alloying constituents as well as C. Principally, these consist of P, Ni and As, which can all be expected to be sometimes present (usually not together) in bloomery iron artefacts.

As described above, the bloom must first be carefully consolidated while still hot to remove much of the remaining slag and enable the iron to fuse together before further heating and forging. This results in hammer-weldable bars or billets (semi-products) of metallic iron (Pleiner, 2006). Although it is clear from metallographic studies that the majority of (general-purpose) iron made by the direct or bloomery process did not contain much C, it is also likely—from early in the Iron Age—that the bloomery process developed more specialized or more heavily reduced variants aimed at producing steel (generally iron with 0.3–0.9% C). P and As are easily recognizable (as paler parts) in iron during metallography and often occur as alloying constituents in bloomery iron—as these elements reduce readily with iron during bloomery smelting. Although little metallographic work specifically to identify recycled iron has so far been done, the presence and distribution of these minor elements may eventually help to identify the occurrence of recycled metal in early artefacts.

P and C tend to be mutually exclusive as (solid solution) alloying components in bloomery iron—a property that was exploited for pattern welding (Gilmour, 2017). P is present to a varying extent in many iron ore sources and will tend to partition with the iron during smelting. C is also likely to be present—but irregularly dispersed—in most bloomery iron due to varying reducing conditions during smelting, but not where phosphoric iron ores have been smelted. Except for specific uses such as in pattern welding, these two forms or alloys of Fe are usually exploited separately. But because they have very different optical properties and if the metals are combined, as during recycling, then the distortions inherent in recycling are much easier to see when a particular piece of iron is being examined metallographically. As is similar in its effects, although it is much rarer as an impurity in iron. Both P and As give rise to bright white areas/banding in iron, which will become distorted during recycling, but will still remain distinct and therefore potentially be useful recycling markers.

During the late Middle Ages, bloomery iron smelting furnaces became larger and more specialized, which led to the development of the blast furnace, in which the primary product was liquid iron rather than a semi-solid iron 'bloom'. This process introduced much more C into the iron during smelting, the progressive take-up of which resulted in the lowering of the melting point until it became liquid. On cooling, this solidified as 'cast' iron—a harder, more brittle and less malleable Fe-C alloy (Baumeister, 2004; Rollason, 1973). A variety of iron ores were used for the indirect smelting method, often involving P-rich iron ores, which reduced the melting point of the cast iron still further, thus making casting easier. However, forgeable iron was the main aim of this new process, so in Europe the resulting C-rich cast iron went through the 'finery' process to turn it into forgeable or 'wrought' iron (wrought iron being a specific reference to decarburized cast iron). For this process, the cast ('pig') iron was broken up and placed in a specialized form of furnace—a 'fining' hearth. These operated under highly oxidizing conditions to remove the C from the cast iron, resulting in virtually C-free 'wrought' iron. Generally, it was later that cast iron was used for the making of ordnance, vessels, firebacks, etc. (Hodgkinson, 2010; Schubert, 1957). This was a late medieval development in mainland Europe and appears to have been operating in Britain by *c.*1490 (Schubert, 1957).

By contrast, in China, the production of cast iron was carried out from at least as early as the sixth century BCE to create a wide variety of objects, including bridges, statues, bells, agricultural implements and small decorative items (Needham, 1958; Wagner, 1993). This early appearance of cast iron has obvious implications for the subsequent recycling of (broken up) earlier cast-iron artefacts in the production of new cast-iron metal. From archaeological evidence, Qian and Huang (2021) claim the earliest cast-iron production in China to have occurred during the Zhou dynasty, *c*.800 BCE, and they also claim the earlier presence of bloomery iron in western China (Xinjiang and Gansu provinces) from as early as the 14th century BCE onwards (during the Shang dynasty of central China). If this is correct, it suggests that bloomery iron in China might be approximately contemporaneous with its presence in Europe.

These two primary forms of iron—cast iron or bloomery iron (or steel)—are very different in their structure and physical properties, so metallography is by far the simplest method to tell the two apart. Cast iron typically has a very high C content of around 4%, as compared with directly produced steel, a highly specialized bloomery product, the C content of which rarely exceeded 0.9%. The C content of most bloomery iron is much lower—rarely exceeding 0.2%, but is characteristically variable below this figure, this being a by-product of the bloomery process. Bloomery iron—because it is the end product of the earlier and less efficient process where the iron was never molten—is nearly always left with characteristic slag inclusions in the metal, which are visible when viewing the microstructures (Pleiner, 2006; Tylecote & Gilmour, 1986).

The chemical composition of non-metallic inclusions in iron artefacts can also provide information on the smelting and post-smelting processes applied during production. It is perhaps the best way to tell the difference between (low C) bloomery iron and 'fined' or 'wrought' iron, the latter made by decarburizing cast iron (Dillmann & L'Héritier, 2007). This was demonstrated on a group of iron objects identified as product intermediaries from a royal tomb at Gyeongju, the capital of the Silla state in Korea, *c*.300–668 CE. Metallography identified two groups of inclusions corresponding uniquely to slags derived from smelting in bloomery furnaces and blast furnaces (Park, 2022).

Bearing in mind these two very different manufacturing processes, we can hypothesize several modes of recycling for iron:

- *Reforging*. Any scrap bloomery iron can, in principle, be reforged by a blacksmith to create a new object or to produce a component of a composite iron object (such as the soft iron core of a knife, to which is welded a (primary) steel cutting edge). This forging together of components is part of the normal practice of the blacksmith and probably represents the dominant form of recycling for wrought iron. It should be noted, however, that such reforging is not without challenges. It is likely to be used in a reductive sense—the final object being smaller than the original, as is illustrated by the *Graisida* spearhead described above. Additionally, every cycle of heating of iron inevitably results in significant loss of metal mass, as shown by Soulignac and Serneels (2014). Such losses, especially if dealing with rusted iron, potentially mean that recycling iron in this way is not as easy as it is for other metals. This form of recycling is most likely seen, as shown below, by careful visual and metallographic examination of the object or by X-radiography.
- *Remelting*. Where cast iron can be produced, the possibility exists of simply remelting and recasting scrap cast iron to produce a new object. This is analogous to the way copper is recycled and is probably the simplest way of recycling cast iron. The identification of such a process for iron could be very difficult to identify, unless partially processed material is found, or through careful archaeological investigation of the melting site. Although in principle a certain amount of bloomery or (fined) wrought iron could be added to the melt for recasting, the much higher melting point of forgeable iron means that this method is less feasible and such a model for recycling is less likely.
- *Re-smelting*. Scrap iron together with fresh ore could be introduced into the bloomery or blast furnace to produce new metal, the scrap metal subsequently being indistinguishably included in the newly smelted product. This could be a way of recycling cast iron, but also presents a major challenge in terms of identification. It could equally apply to bloomery or wrought

iron, but seems unlikely for the reasons given above, unless it was seen as a way of reprocessing completely rusted iron.

- *Transformation*. There is particular complexity in ferrous metallurgy when compared with, say, copper, in that transformation between different states of iron (cast iron to wrought, via finery, or to steel by partially removing C from cast iron) may or may not involve recycling in the strict sense of the word, depending on whether the cast iron to be processed is fresh from the blast furnace (pig iron) or is reused from elsewhere. In medieval Mongolia, for example, Park et al. (2019) show how cast iron (possibly from China) was converted into steel on a very small scale by heating pieces of cast iron to decarburize in the semi-molten state. This method was probably developed by these mobile horsemen as an adaptation to the constant need for steel and is arguably an example of a recycling (as well as a transformational) process.

REFORGING OF BLOOMERY IRON

The implications of the historical records discussed above for the hoarding of scrap iron at the blacksmith's forge is that this metal was to be reforged. Reforging iron, independently of where the ore was originally smelted, will reduce the volume of slag inclusions within that piece of iron. But the efficiency of such inclusion removal is dependent upon both the blacksmith performing the work and the volume of slag inclusions present in the iron initially, which can vary greatly. The depletion of slag inclusions is not proportional to any other aspects of the metallurgy and, therefore, is not a marker for iron recycling that can be measured. In future, it might be profitable to analyse the individual inclusions within suspected recycled objects to assess the variation in their composition within each object. Although the complete corrosion of iron usually makes metallographic study difficult (if not impossible), it is sometimes possible to extract slag inclusions that can be chemically analysed (e.g., Stepanov et al., 2020).

Although reforging can mechanically reduce the volume of slag inclusions in bloomery iron, the chemical changes as a result of forging are less easy to quantify. Rostoker and Bronson (1990: 86) asserted that heating and forging during the fabrication of an object from bloomery iron does not chemically change the slag inclusions. But this is potentially an oversimplification, given that Disser et al. (2020) have demonstrated that the forging process can both mechanically fracture slag inclusions in bloomery iron and potentially induce new compositions of slag where additional fluxes have been used in the forging process. Furthermore, Park (2022) suggests that inclusions in bloomery iron can undergo some chemical and microstructural changes under certain circumstances, for instance, during the production or processing of a steely bloom (see also Blakelock et al., 2009). It is also possible that case carburization (also known as case hardening) may be found in a few cases such as early files or rasps, as in the case of one Iron Age file from Gussage All Saints, Dorset—made first of low-C bloomery iron but then 'baked' in carbonaceous material (and possibly quenched) to give a very steely surface layer to make the file more effective (Fell, 1985). However, iron does not absorb C readily, even when very hot under heavily reducing conditions (Tylecote & Gilmour, 1986: 16, fig. 5), and therefore, early bloomery steel can always be expected to be a smelting phenomenon and product.

There is clearly a complex relationship between slag inclusion chemistry, mineralogy and microstructure resulting from smelting and post-smelting processing. Careful metallography may often reveal relict or distorted structures due to the reforging of scrap iron, particularly if physically distinct from other iron in the object.

In his fantasy trilogy *The Lord of the Rings* (1954), J. R. R. Tolkien describes how the longsword named *Narsil* was used by King Elendil's son, Isildur, during the War of the Last Alliance to cut the One Ring from Sauron's hand. In so doing, the sword was shattered into pieces, and was known in legend as 'the sword that was broken', but was subsequently reforged for Aragorn, heir to the Kings of the West, by elven smiths to become the Flame of the West. It is unknown what inspired Tolkien (an Anglo-Saxon and Viking/Norse specialist at Oxford) to describe this reforging of the 'sword that was broken', but one possibility is the Norse legend of the smith Velent or Wayland, who is said to have ground down an old (?damaged) sword from which he forged a new blade (Ellis Davidson, 1994: 127). In practice, as described, this would have been impossible to achieve technically, but this story may just be a somewhat exaggerated echo of such a happening. However, reuse by reforging is likely to have been more common but much less prosaic for other iron artefacts. But finding examples is not so easy, largely because—when compared with how much non-ferrous metalwork has been analysed—so little archaeological ironwork has been examined to see how it was made, and what form of iron was the starting point.

As far as we are aware, no example of a reforged sword has ever been recognized, although it would take both careful X-ray and metallographic study to identify it. One might also suggest that the breaking up and reforging of a sword blade may be inherently unlikely because the physical properties of the sword blade would no longer be predicable, and this is essential for something long and narrow such as a sword to actually work successfully (unless purely decorative). Except in the case of all steel blades, nearly all pre-modern sword blades that have been structurally examined have been found to have carefully assembled composite, sometimes heat-treated, blades where each part of the composite has a specific function (hardness, toughness, flexibility, surface appearance, etc.). Once a sword blade such as this is broken up (no mean feat) and reforged from pieces, then the known combination of properties is likely to be lost, unless the resultant surface pattern inherent in this reforging was the purpose in the first place.

However, five examples of the use of recycled iron were found in a recent metallographic study of ironwork from the fifth to eighth centuries CE Anglo-Saxon cemetery at Eriswell in Suffolk (Gilmour, forthcoming). Our criterion for identifying recycled iron is that if the section in question shows distortion consistent with an earlier object being reworked, then we interpret it as being reused (recycled) from an earlier object. This is, of course, a matter of interpretation, which needs to be informed by extensive experience of looking at archaeological iron objects. Intrinsically, this need for interpretation indicates why studying recycled iron is so difficult. The first was a spearhead from Grave 265, which was made from many small pieces of—in this case plain, almost C-free—iron. Some 30 separate pieces are present in one transverse section alone (Figure 3). Technically, this may have been difficult, necessitating the use of an Fe silicate-rich flux, which we see in section marking the boundaries between the separate pieces. The use of very low-C iron suggests this was not made of a broken-up sword blade, but small pieces from one or more different artefacts. The apparent use of flux may have been done intentionally to improve/exploit the surface appearance after final polishing and etching. Another two of the other four examples of recycled iron from the Eriswell cemetery—a spearhead (Figure 4) and a knife (Figure 5)—both came from Burial 313. The other two were a spearhead (from Burial 215) and a knife (Burial 5).

An unusual earlier instance of the use of recycled iron was found during the routine metallographic examination of a small broken iron knife from the Romano-British predecessor of the Oxfordshire village of Yarnton (Figure 6). In section, it was clear that a segment (at least) or complete worn-out earlier knife had been welded onto a strip also made of reforged recycled iron to form the main body of the new knife to which a fresh (unrecycled) steel cutting edge had also been butt-welded (Figure 6). It was also clear that the earlier knife—itself made of an iron–steel–iron sandwich—had been rendered all but useless by incorrect/asymmetrical sharpening that had left steel core of the sandwich isolated towards one side (Gilmour, 2011: 462–467).

We can thus see that iron was indeed recycled in predicable ways. Sometimes, broken fragments, for instance, of sword blades, were refashioned into smaller objects—Anglo-Saxon examples including spearheads and so-called weaving battens (Gilmour, 1990: appx 1, nos 141, 310, 319). These examples involved the trimming or filing down of the blade fragments

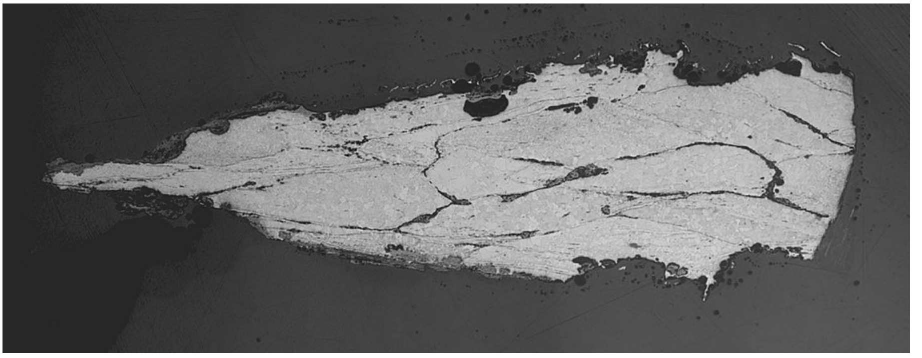

FIGURE 3 Recycled iron pieces used (with flux) for the spearhead from Eriswell A-S burial 265. This photomacrograph shows the section to consist of approximately 17 separate pieces, each consisting of very low carbon or plain iron, the welds here being emphasized by very visible lines of entrapped (iron oxide/iron silicate) slag. The section is 16 mm wide and etched with 2% nital.

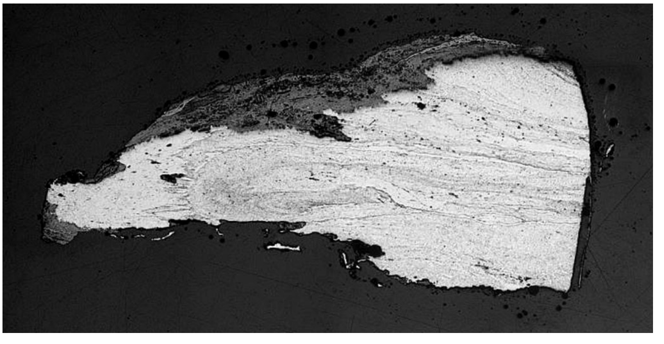

FIGURE 4 Recycled iron forms the main bulk of this spearhead from Eriswell Grave 313, which in section shows a multiple banded structure to much of the spearhead with a separate weld-on edge piece. There are approximately six individual roughly horizontal bands visible here each one separated from the next by a weld marked here by very narrow, more or less continuous whitish lines. The section is 15 mm wide and etched with 2% nital.

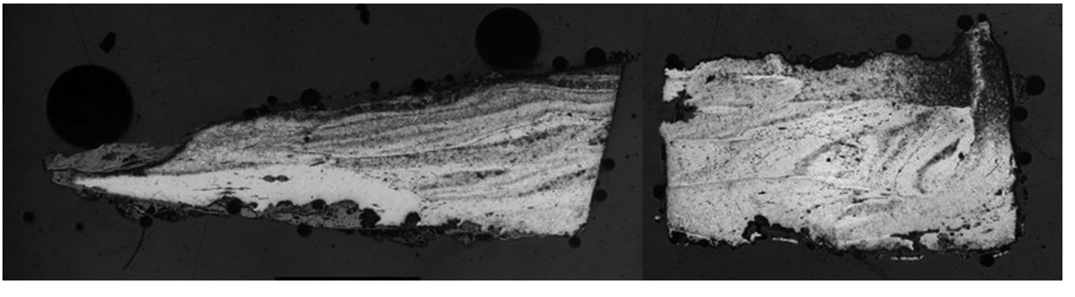

FIGURE 5 A composite overall section—made up of cutting edge and back parts—of a knife from Eriswell Burial 313, mostly consisting of recycled iron. Overall, the section is made up of about ten individual parts welded together; these individual parts themselves variously consisting of contorted mixtures of (pale etching) plain iron, (very pale etching) phosphoric iron, (grey-etching) low-carbon iron and (very dark grey/black etching) steel. The total length of the transverse section is approximately 13 mm, and it is etched with 2% nital.

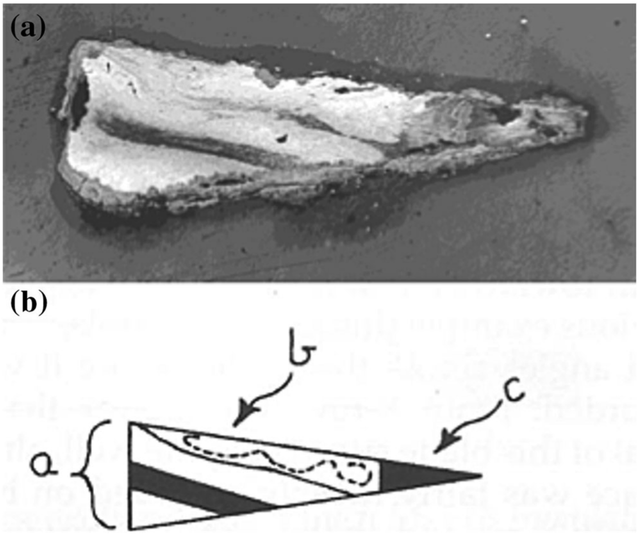

FIGURE 6 (a) Photo-macrograph showing that (in section) the lower two-thirds of a Yarnton R-B knife are made up of an earlier recycled knife to which additional recycled iron has been welded to form the core and back part of the blade, to which a piece of (unrecycled) steel was welded to form the cutting edge (Gilmour, 2011: figs 15.17–15.18). (b) Simplified diagrammatic sketch showing the different parts visible in section

and the partial reworking of one end to provide makeshift sockets or handles. The spearhead from Burial 265 at the early Anglo-Saxon cemetery at Eriswell is an echo of what Tolkien describes for the reworking of fragments from the fictional sword *Narsil*, as well as the similar tradition of Velent or Wayland (see above).

But how old is this tradition? A possible great antiquity is suggested by the fact that the Eriswell blade in Burial 265 fits no sword blade attributable to any period later than the Iron Age, whereas various late Iron Age swords appear to have been made in a way consistent with this description, such as the two swords from Orton Meadows, Cambridgeshire, and another from Shepperton, Surrey (Stead, 2006: 46–47, pl. 6). It is clear from their differentially etched surfaces, which are at least partly original as opposed to being a corrosion effect, that these swords were made from multiple small pieces. Before the assembly of each sword blade, these pieces may have been drawn out to form bundles before being welded together. As far as we know, only one sword of this kind has been analysed metallographically—and found to have a structure consistent with the use of recycled iron—and that is a fragment of another late Iron Age sword this time found in the River Thames at Long Wittenham, Oxfordshire (Gilmour, 1990: 71, fig. 15; Tylecote & Gilmour, 1986: 162, fig. 66). Thus, it may have been the use of recycled iron in this way in the late Iron Age that led to more formalized pattern welding that did not involve the use of recycled iron (Gilmour, 1990: fig. 76, 1b).

REUSE OF SCRAP BLOOMERY IRON FOR SPIRITUAL REASONS

Sometimes, it is possible to identify the reuse of scrap iron for spiritual rather than technical reasons. Just such a case was noticed by one of the authors (MP) on a visit to one of the few remaining traditional swordsmiths in Japan some 20 years ago. He noticed a wooden box of iron nails near the smith's hearth for forging the iron. On asking, the swordsmith said that they were nails recovered from an old Buddhist temple and were used in the manufacture of the iron for the sword to bring spiritual benefit. Some 10 years earlier, another of the authors

(BG) spent a week at the forge of the same master swordsmith (Kawachi Kunihira). He explained how the process of choosing the different grades of iron and steel is done, as well as how the swords are put together, with each master smith having his own method for assembling and finishing the blades. He explained how both the harder steel and softer iron parts of these composite blades come from the same firing of the one remaining traditional *tatara* iron-making furnace—the last remaining bloomery furnace to have come down to us in an unbroken sequence from antiquity (as opposed to a more modern reconstruction). It is highly likely that such recycling as described above is largely invisible in the final product, unless (as discussed above) the reused pieces contain unusual levels of other elements not removed during the process, the most likely being P, As or Ni (Tylecote & Gilmour, 1986). In any case, it is likely that only a small proportion of scrap iron such as this would have been included, and it would have been incorporated into the soft iron parts of a composite weapon such as a Japanese sword. This example, albeit for a very special product, shows how non-practical considerations may have been responsible for some recycling practices. It is not hard to imagine that similar considerations may have applied in the past to other special items, such as the *Graisida* spear.

CONCLUSIONS

With substantial chemical evidence for the recycling of other materials in the past, and the historical evidence for hoarding and trading scrap iron, we should assume that past communities also recycled iron, perhaps on a scale similar to the 10% plus proposed by Woodward (1985) for post-medieval ironworking. However, few medieval and earlier iron artefacts appear to have been examined to look for evidence of recycling. In one assemblage at the fifth to seventh centuries CE Anglo-Saxon cemetery at Eriswell (Suffolk), recycled iron was found to have been used in five out of the 28 iron artefacts metallographically examined, thus being nearly 20% of the total and supporting Woodward's suggestion that recycled iron formed 'considerably more than ten per cent of a blacksmith's raw materials' (p, 186).

The likely use of recycled iron in late Iron Age swords in Northern Europe may also help explain the origin of the Viking Age tradition of the mythical smith Velent or Wayland having 'filed down' an old sword and forging a new one. Given that this tradition may have come from reports possibly as much as a millennium earlier, we can expect that the detail in the oral tradition had become garbled or exaggerated from much retelling.

Although recycled iron may not have been used in swords after the late Iron Age, its use has been noted in Roman and medieval knives and spearheads, as in the case of a small Roman knife excavated at Yarnton that included part of the blade from another small knife, to which more recycled iron had been added to one side, before a steel cutting edge was welded to this body to create a new knife. Two iron artefacts found in Burial 313 at Eriswell—a spearhead and knife—were both found to be made largely from recycled iron. Also from Eriswell, another spearhead was found (in Burial 215) to be made from many small pieces of recycled iron, echoing the Norse legend of Wayland reforging a fragmentary sword, which may be a folk memory of a late Iron Age sword-making practice.

Much more metallographic work needs to be carried out to demonstrate how common iron recycling actually was, as well as to find out the different ways it was done. However, even though the sample base from which our conclusions have come is as yet small, it seems reasonable to conclude that iron recycling can be expected in perhaps 20% of cases, much as concluded by Woodward (1985). Other forms of recycling, as hypothesized above, are more difficult to observe, and much more work is required to see if any are evidenced in the archaeological record.

DATA AVAILABILITY STATEMENT

Data sharing not applicable to this article as no datasets were generated or analysed during the study.

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ENDNOTE

[1] From the Anglo-Saxon *bloma* or 'flower', presumably referring to its appearance in the furnace.

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