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A Germanic ultrahigh carbon steel punch of the Late Roman-Iron Age

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Abstract

Chemical and microstructural analysis of Late Roman-Iron Age iron objects from the Germanic site of Heeten in the Eastern Netherlands has led to the identification of an early example of a finished artefact of ultrahigh carbon steel. The results presented here make it necessary to reconsider the established views that extremely high carbon steel technology was of uniquely Near Eastern or Asian origin, and that simple unalloyed iron was the only intended product of the ancient iron bloomery smelting process.

Keywords: Archaeometallurgy; Germanic iron smithing; Ultrahigh carbon steel; Phosphoric iron; Bloomery; Slag-pit furnace

1. Introduction

Metallographic examination of archaeological iron artefacts from the Late Roman-Iron Age site of Heeten (2nd to 4th/5th centuries AD) in the Eastern Netherlands has led to the identification of a very early example of a tool manufactured from ultrahigh carbon steel. The Germanic settlement and iron smelting site at Heeten (municipality of Raalte, Province of Overijssel) was excavated by the Dutch State Service for Archaeological Investigations (ROB) in 1993–1994 [14]. Ten iron artefacts from the site were selected for metallographic and chemical analysis by scanning electron microscopy (SEM-EDS) and electron probe microanalysis (EPMA). Eight of the artefacts analysed, all nails and rods, were phosphoric iron alloys in the composition range 0.1% to 0.8% phosphorus, and phosphoric steel alloys of the same phosphorus content range plus up to 0.8% carbon. A ninth object, a semi-finished rod, was made of low carbon steel of 0.1% to 0.2% carbon, and contained arsenic-rich weld lines (the presence of arsenic was detected but not quantified by EPMA). This object was phosphorus-free. The tenth artefact, and the only tool to be analysed from the site, was a punch (Fig. 1), and this was found to be an extremely high quality phosphorus-free steel object, with an overall composition of around 2% carbon. As such, it is ultrahigh carbon steel, an alloy that has not previously been recognised in a functional, finished object of the period. The evidence may reflect a Germanic tradition of technological ability in the selection and manipulation of raw materials, and in the forging of iron, that was unmatched by Roman smiths.

2. Cast iron, crucible steel, and ultrahigh carbon steel

Discussion of ultrahigh carbon steel in the archaeometallurgical literature has tended to be interlinked with discussion of liquid-state iron production technology of Southeast Asian, Indian and Near Eastern origin. In India, production of cast iron in the form of crucible steel, also known as Wootz, can be traced back to the 3rd century BC, based on literary references and crucible remains [1]. However, finished objects with especially high carbon content are rare in early periods, and indeed are not really found before the 7th century AD. Most

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Fig. 1. The Heeten punch.

ultrahigh carbon steel artefacts cited in the literature are associated with Early Islamic crucible steel processes. In China, cast iron technology extends back even further, perhaps to the 6th century BC [15]. But again, the capability to produce cast iron (up to 4.3% carbon) is not accompanied by the appearance in the archaeological record of many finished artefacts in the ultrahigh carbon steel (1.5–2.1% carbon) range.

The early emergence of iron casting technology in China, combined with assorted references in classical Greek and Roman literature that can be interpreted as suggesting familiarity with liquid-state ironmaking technology, has long led archaeologists to look to the East for the inspiration of European iron casting technology and along with that, the earliest ultrahigh carbon steel.

It is certainly true that Roman-era trading contacts with India and China involved exchange in iron. Pliny the Elder (23–79 AD) observed that the best iron in the (Roman) world was sent by the Chinese, along with cloth and animal hides, and that the Parthians sent the second best iron. Pliny specifies that the distinction of the Chinese and Parthian varieties of iron is that they alone are "…tempered from pure steel, whereas all the others have a softer complement mixed in with them". *Nat. Hist.* Bk. 34, XLI-145 (Authors' translation). It is open to debate whether, in this reference, Pliny is comparing solid ingots of brittle cast iron from the East with the more malleable, low carbon, bloomery iron produced in the West.

Whatever the case for East–West iron casting technological transfer, archaeological evidence has recently been emerging for the processing of cast iron within the Roman world, if not as far back as Pliny's time, then at least to the 5th/6th centuries AD. Tizzoni and Tizzoni [13] report the find of a 3.5 kg lump of processed white cast iron from an iron smelting and forging site in northern Italy. Although small quantities of cast iron and high carbon steel have been recognised as a by-product of bloomery smelting for some time, the unusual aspect of this find is that it was closely associated with a fully-formed artefact, a mining chisel, that is identified by Fluzin [2] as having been produced from processed, decarburised cast iron. However, the carbon content of the chisel was found to be 0.8%, which is the standard eutectoid composition of steel, so again it is not evidence for a finished object of either cast iron or ultrahigh carbon steel.

The ultimate use of ultrahigh carbon steel in finished functional objects of the Roman-Iron Age has up to now been undocumented. What is now evident from the Heeten punch is that excellent quality ultrahigh carbon steel was certainly being used in toolmaking in Europe by Germanic tribes, at least from the Late Roman-Iron Age. Here it is argued that, rather than being a liquid-state or cast iron process, the manufacturing technology was solid-state, involving either carburisation of iron at the smelting stage, in a bloomery furnace, or a very high temperature forge-carburisation process that is previously unattested in Europe. The technology represented by the Heeten punch could be a northern European innovation, unconnected with Roman iron-making practices or with any cast iron or crucible steel technology.

3. Heeten

The site of Heeten is located approximately 50 km north of the River Rhine, which formed a natural border with the Roman Empire. Intensive iron production at Heeten was probably confined to the 25 year period of 315 to 340 AD, and may even have been limited to a few years within this time [4]. The movement of Germanic tribes in the region, and the increased demand for iron, e.g. in the form of tools and weapons, can be related to the instability surrounding the 4th/5th century AD collapse of Roman control in Western Europe.

Iron smelting technology as practiced within the Roman Empire typically involved tapping molten slag out of the side of the bloomery furnace. Inside the furnace, an iron 'bloom' would amass in the solid state. After a smelt, the bloom would be removed and the furnace could be repaired or re-lined if necessary, and re-used. The iron smelting method used by contemporary Germanic people on the other hand represented a distinct, and extremely coherent, cultural phenomenon. At Heeten, as at other Germanic iron production sites, local high-phosphorus bog iron ore was smelted in furnaces where the slag collected in a pit directly underneath the furnace shaft. In this type of furnace, the solidified content of a pit is thought to represent the slag residue from a single smelting session. A new pit would be dug for each subsequent smelt. It is estimated that there are around 1000 furnace pits at the site of Heeten ([4: p. 203]). The furnaces would have been operated at a temperature of at least 1200 °C, in order to produce a molten slag that would separate from the solid iron bloom. This temperature would also be necessary to achieve full reduction and agglomeration of the metallic iron. One example of a complete slag block, which weighed 30 kg, was recovered from the site of Heeten. A complete 7.5 kg iron bloom was also found, which consisted of metal with inclusions of slag and fragments of stone and charcoal. The microstructure of the bloom is discussed in more detail below.

The quantity of 4th century AD iron production at Heeten signifies an output that was clearly surplus to local requirements [7]. In contemporary settlements of the region, slag-pit furnaces are often found, but only in concentrations sufficient to fulfil the needs of the community ([10: p. 115]). Across northern Germany and Denmark, there are other Germanic pit-furnace sites comparable in magnitude to Heeten. These sites seem to have been producing similar amounts of iron, but over a longer span of time [5,6,11].

Heeten appears to have been a specialised production site. The slag assemblage included only a small amount of residues that could be associated with the initial working of blooms down to iron billets or bars. A contemporary site with a conversely high proportion of slag deriving from bloom smithing was identified 4 km away [4: pp. 206–208]. Archaeobotanical and zoological research also indicate good organisation of the iron industry at Heeten: large amounts of processed cereals, mainly rye, and cattle were imported to the site in the first half of the 4th century AD [9]. Most of the industrial activity at Heeten took place outside of an enclosed settlement area. Some iron forging did however take place within the settlement, as a smithy was identified in the south-eastern corner of the site, along with a concentration of other small buildings that may have functioned as storerooms. The iron artefacts discussed here were found mainly in this area.

Nails accounted for the majority of the 4th century AD iron artefacts from Heeten. Although a common find within Roman territory, nails are very rare in the Germanic domain. Heeten is only the second Germanic site in the Netherlands where nails have been found in securely dated contexts. The Heeten bloom, all of the nails, and one semi-finished rod from the site were phosphoric iron, in some cases carburised to form phosphoric steel. Two other of the Heeten artefacts proved to be phosphorus-free steel: a further semi-finished rod, and the ultrahigh carbon steel punch discussed here.

The Heeten punch was recovered in a very complete state of preservation from the waterlogged filling of a well. The construction wood of the well has been dated by dendrochronology to 316 AD. The well had been filled in by at least 345 AD. An 80–120 cm thick agricultural layer (Plaggen soil) that began accumulating in the 12th–13th century AD, covers the site, making intrusion of later artefacts extremely unlikely. There is an absence of habitation at the site of Heeten between the 5th and 11th centuries AD.

4. The Heeten punch

The Heeten punch measures 6 cm in length and 1 cm in maximum thickness, tapering to a point (Fig. 2). The object is roughly square in transverse section and has a slightly flared top. The punch is a tool of solid steel, formed by longitudinal welding of three strips of through-carburised metal, approximately 3 mm each in thickness (Fig. 3). Slag inclusions are present along weld lines, in some very fine stringers, and in a few concentrations of randomly orientated particles (Fig. 4). Some decarburisation has occurred along the length of the welds (detail, Fig. 5), producing a striped surface pattern that is visible to the naked eye.

The microstructure in the upper portion of the punch comprises coarse pearlite grains with iron carbide (cementite) needles, indicating that it has been cooled slowly in the hearth (Fig. 6). There is a network of cementite at the grain boundaries (detail, Fig. 7). Faster cooling, for example in air at room temperature, would have resulted in a substantially smaller grain size, in theory increasing the toughness of the metal. However, this portion of the punch, the upper shaft, is not the working end of the tool, so the large grain size seen here may not have had an adverse affect on the functionality of the object. As detailed below, the pointed end of the punch has in fact been extensively heat-treated.

When etched with Oberhoffer's and Stead's Reagents, several restricted areas of the shaft microstructure show a mottled effect caused by segregation of trace elements.

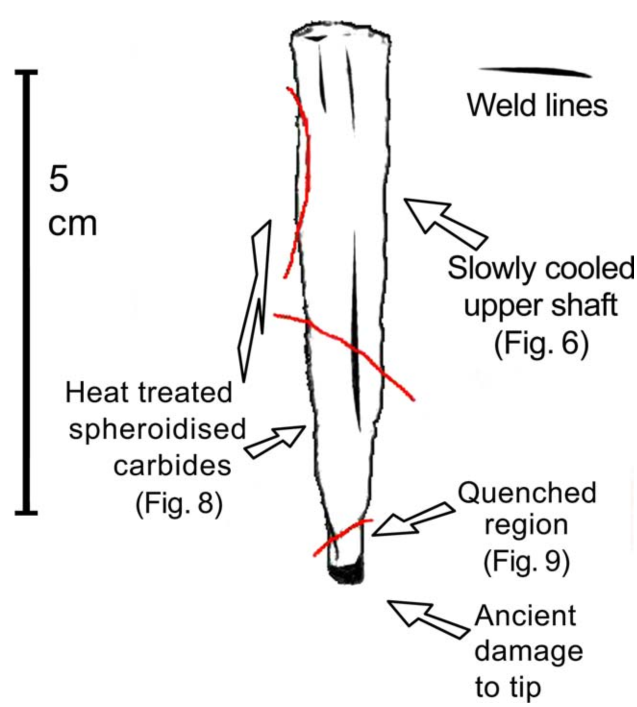

Fig. 2. Construction of the Heeten punch.

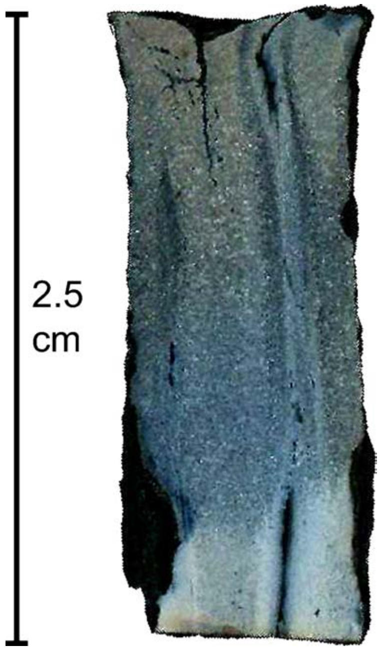

Fig. 3. Flared top end of the punch: the welds are accentuated by corrosion. The lengthwise-banded surface pattern that has resulted from decarburisation during welding is particularly clear along the right-hand weld line. (Upper 3/4 etched with 2% Nital.)

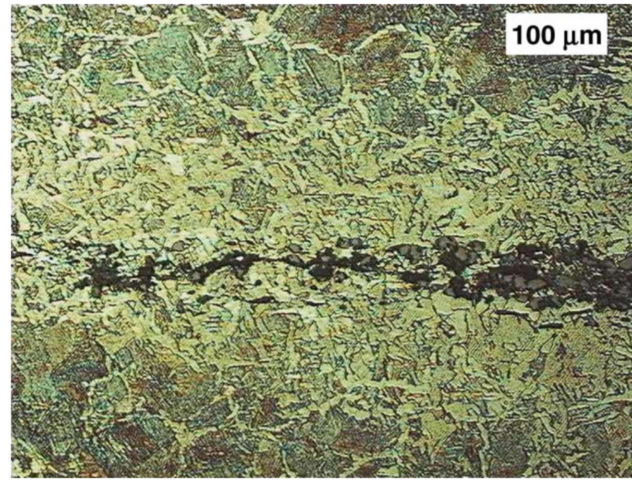

Fig. 5. Corroded weld near top end of the punch: detail of decarburisation along one of the two major welds. (Etched with 2% Nital.)

An overall banded etching effect, following the lengthways direction of forging, also appears. No phosphorus at all was detected in the metal, either by SEM-EDS analysis, or by EPMA. Analysis suggested that these etching effects might be the result of the presence of very low concentrations of arsenic.

The lower portion of the shaft of the punch has undergone prolonged heating and substantial high-temperature working, as indicated by extensive regions of broken-up and spheroidised carbides (Fig. 8). It may be that the point of the tool was quenched in water, but this is not certain, as unfortunately the very tip is missing. The nature of the break and the pattern of the immediately adhering corrosion layer suggest that the damage occurred in antiquity. The microstructure of what survives of the tip indicates that it has been cooled much more rapidly than the rest of the punch, possibly by slack-quenching in oil (Fig. 9). It may equally be that it was quenched in water and then extensively tempered afterwards. Either of these possibilities would demonstrate an understanding on the part of the smith of how to produce a tool of maximum strength and minimum brittleness. Vickers microhardness values along the shaft of the punch are consistent, averaging 326 HV. In the area near to where the tip has broken off, the microhardness ranges from 364 HV to 409 HV. By

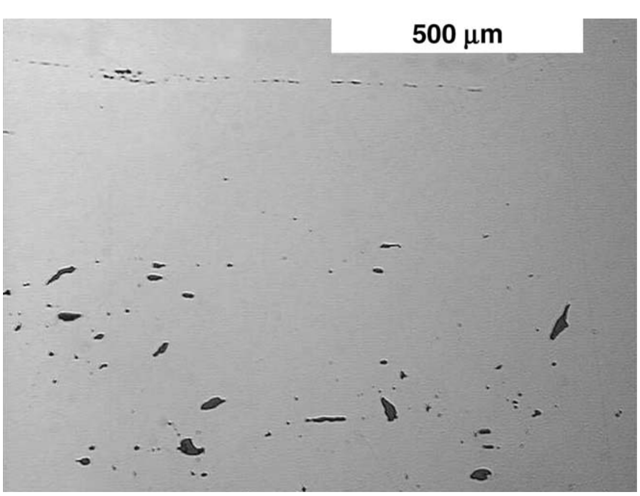

Fig. 4. Slag inclusions: fine slag stringer along the top, and randomly orientated particles in bottom half of micrograph. (Unetched.)

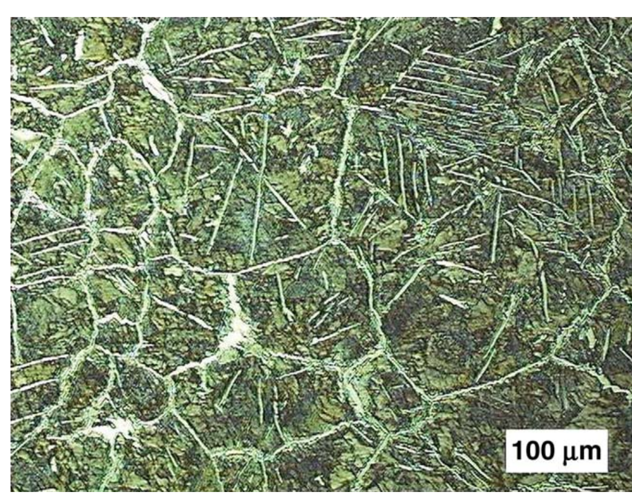

Fig. 6. Upper shaft of the punch: microstructure of coarse pearlite grains with cementite needles. (Etched with 2% Nital.)

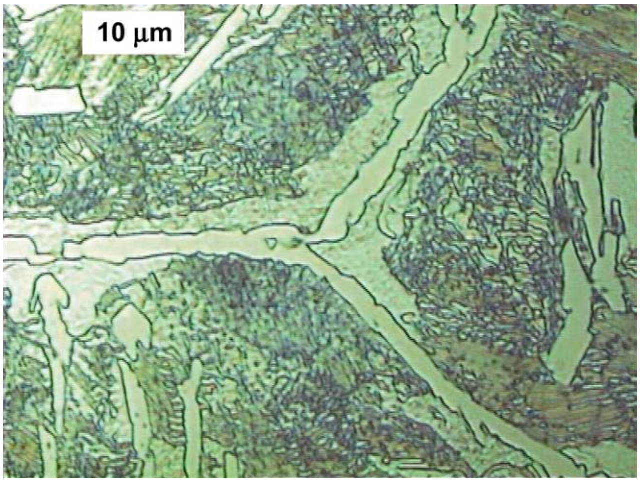

Fig. 7. Detail of grain boundary: inner cream-coloured cementite, surrounded by white iron phase. (Etched with 2% Nital.)

comparison, quenched but *not tempered* medium to high carbon steel can have microhardness values above 800 HV, but would be very brittle. Iron that has not been carburised would be considerably less hard than the punch, with values generally in the region of 100–180 HV.

5. Ultrahigh carbon steel

The Heeten punch is determined by metallography to contain around 2% carbon. This carbon content is at the maximum of what is physically possible to achieve by diffusion in the solid state, and is on the borderline of what would have to have been produced in the liquid state, i.e. cast iron. Archaeological artefacts of ultrahigh

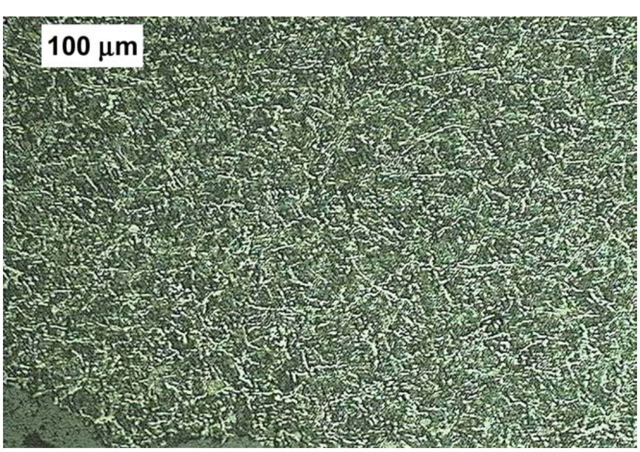

Fig. 8. Lower shaft of the punch: broken-up and spheroidised carbides. Note that the scale is the same as in Fig. 6, but the microstructure is completely altered by high temperature processing. (Etched with Stead's Reagent.)

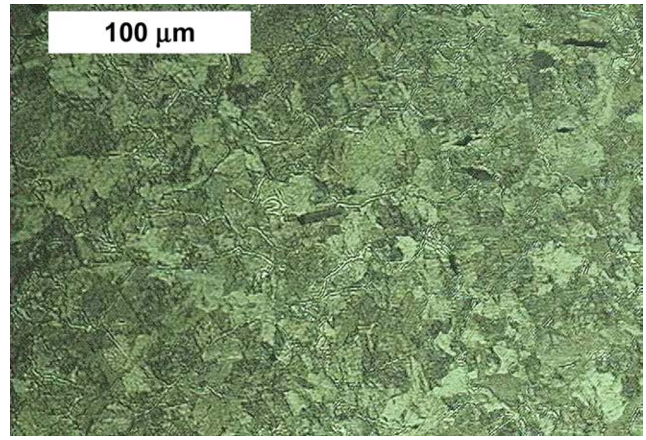

Fig. 9. Tip of the punch: quenched area in the tip of the punch, near to the break. (Etched with 2% Nital.)

carbon steel such as this are not at all common. To the best of the authors' knowledge, the punch represents the earliest example of a finished object of this composition from Europe.

Ultrahigh carbon steel (1.5–2.1% carbon) is in fact a rarity even in modern industrial applications. Metal between the usual carbon steel (0.1–1.5% carbon) and cast iron (2.1–4.3% carbon) ranges has been ignored because of the tendency of large amounts of cementite to form grain boundary networks, causing brittleness that makes the metal unacceptable for modern commercial fabrication. Research in the past 25 years has shown how this effect can be overcome, producing a material noted by the researchers to have a strong resemblance to Early Medieval crucible steel [12].

In modern processes, high carbon steel is produced by decarburisation from a liquid melt. A prohibitively high temperature of around 1390 °C is required to make 2.1% carbon cast iron directly. It is easier and more economical to produce cast iron at 4.3% carbon, as the melting point of the alloy drops to around 1150 °C; the metal can then be decarburised, in a liquid or semi-molten state, to the desired composition.

The conventional archaeological understanding is that cast iron smelting technology, with its associated refining and decarburising processes, only came to be developed and widely implemented in Europe in the Middle Ages. Notwithstanding the Sino-Roman connections mentioned earlier, and the 5th/6th century AD example of Tizzoni and Tizzoni [13], there is thus far no evidence for crucibles or cast iron processing remains of the Roman-Iron Age in northern Europe that might indicate Germanic manufacturing of ultrahigh carbon steel by decarburisation from cast iron. It is proposed here that the ultrahigh carbon steel of the Heeten punch was produced not by casting, but by an alternative, solid-state, process.

6. Formation of high carbon steel in a bloomery furnace

Although it is true that the only practical methods of large-scale cast iron smelting, refining, and decarburisation are liquid-state procedures, it is well known from finds of unagglomerated bloom fragments, or 'gromps', that small-scale formation of high carbon steel did often occur in ancient solid-state bloomery furnaces. Gromps are found associated with both iron smelting and smithing remains from the Iron Age onwards, and can have any composition from solid-state iron with no carbon, up to cast iron at 4.3% carbon. They tend to be heterogeneous, and can vary compositionally not just within a particular archaeological assemblage, but also within a single piece.

Gromps are easily recognised amongst other production debris, even though they will have an outer coating of slag, as they are highly magnetic and exceptionally dense compared with slag. Thus, albeit that gromps are normally interpreted as a waste product, and that the occasional cast iron examples are regarded as accidentally produced, it is possible that high carbon pieces could have been carefully selected by ancient metalworkers, for smithing into small portions of steel. Forming a homogeneous, functional object out of such material would however present a challenge. Moreover, if the metal had solidified from a melt of 2.1% carbon or above, then it would be expected that certain liquid-state processing indicators would be present, which extensive solid-state forging would not eliminate completely. The final smithed object may, for example, show a systematic pattern of trace element distribution. No unambiguous solidification features are present in the Heeten punch.

The unworked bloom found at Heeten illustrates how high carbon steel can also be present as a component of an agglomerated iron bloom. It is evident from the morphology of the Heeten bloom that it is a typical solid-state bloomery product. It incorporates large slag inclusions and pieces of stone and charcoal that would have separated as a rim if the whole mass had been molten. There are, however, localised liquid microstructural phases present in the outermost portions of the bloom. Most of the liquid phases seen melt at under 1200 °C: steadite, ferrite/iron carbide/iron phosphide ternary eutectic, and concentrated iron phosphide. But there is also a higher melting point region of solidified 0.7% phosphorus iron, which suggests that the furnace has reached a maximum temperature of around 1400 °C at at least one point during the smelt. Carbon content ranges from zero at the centre of the bloom, which is made up of large-grained ferrite with iron phosphide segregated at the grain boundaries, to areas of eutectoid steel containing 0.5% phosphorus, to portions of up to around 1.5% carbon on the outside of the bloom.

It is clear that when the fluctuating reducing conditions and temperature of a bloomery furnace happen to coincide at a certain point, the 'accidental' production of high carbon steel or even cast iron can occur. It is not surprising that a bloomery furnace can produce metal other than solid-state, carbon-free iron. Due to the very high temperatures and intensely reducing conditions involved, and to the porous nature of ore and metal particles in the midst of reduction, iron is far more susceptible to carbon diffusion in the smelting furnace than it will be afterwards as a mechanically consolidated billet or bar.

The problem with relying on bloomery smelting as a means of production of ultrahigh carbon steel is that, as demonstrated by the Heeten bloom, the result can be very heterogeneous, with products varying in composition even on a microscopic scale. It is difficult to imagine how the highest carbon portions could have been selected from, for example, an unwieldy 7.5 kg solid-state bloom.

While small cast iron gromps, on the other hand, are easily sorted from other materials, the metal smithed from them could still be expected to show some solidification features. Controlling decarburisation, while at the same time avoiding huge metal losses and limiting the final slag content in metal smithed from gromps, would also be quite difficult to manage. If such processing had been undertaken in Europe in the Roman-Iron Age, then certain characteristic residues such as crucibles and refining slags would be expected to have been identified in the archaeological record.

7. Carburisation of bar iron

The alternative and more certain route to ultrahigh carbon steel is by carburisation of iron bars entirely in the solid state. According to modern industrial pack-carburisation practice, i.e. using fluxes, high purity iron, closely controlled temperature and atmosphere conditions, it is possible to achieve a maximum of just over 2% carbon by solid-state diffusion, but it would be expected to take around 50 h to reach a case depth of 4 mm, at 925 °C [16]. This time-span, and the use of any higher temperature, would not be considered to be commercially viable, although of course raising the temperature will increase the rate of solid-state carbon diffusion.

Time and intensity of labour were surely less significant issues in ancient technological procedures than in modern industry. The mechanical energy source used to carry out any high temperature process was literally manpower, i.e. working the bellows, and this is an example of an arduous activity that was once commonplace but would not be contemplated today. Thus, in antiquity, ultrahigh carbon steel could have been manufactured by quite a laborious, solid-state, carburisation method, with extensively forged metal strips being subjected to prolonged heating in a well-controlled atmosphere, perhaps at a temperature in the region of 1200 °C. This could effectively mean the use of an installation more similar to a furnace than a typical open smithing hearth, operated with the purpose of consistently carburising thin strips of iron and producing small quantities of high quality steel.

The Heeten finds did in fact include two examples of thin iron strips, or semi-finished rods, with context numbers 18-1-20-2 (end pointed; length 7 cm; thickness ca. 6 mm) and 23-1-49-43 (end broken off; preserved length 5.5 cm; thickness ca. 6 mm). The rods are both roughly square in cross-section. Rod 23-1-49-43 is phosphoric iron with no visible carbon content. It has an extremely high volume of slag inclusions, suggesting that it was still in the process of being worked-up into a finished object. Rod 18-1-20-2 was found in the same context as the punch (which has an accession number of 18-1-20). This rod was heterogeneously carburised steel of 0.1–0.2% carbon, with no detectable phosphorus content (SEM-EDS analysis). The volume of slag inclusions is not as high as rod 23-1-49-43, but still does exceed that of the finished artefacts from the site. Both rods display small grain size, multiple weld lines, and extensive banding when etched with Oberhoffer's Reagent, which indicate repeated heating, folding and forging of these tiny strips of metal. The phosphorus-free steel rod 18-1-20-2 contains arsenic-rich white weld lines. The arsenic content was detected, but not quantified, by EPMA. Some linear etching effects, also evidently caused by arsenic, and grain boundary films indicative of carbon concentrations of around 0.05%, appear when rod 18-1-20-2 is etched with 2% Nital.

8. Selection and manipulation of ore and metal

It is unexpected to find phosphorus-free metal at a site where iron was being produced from phosphorus-rich ore. A single, finished, phosphorus-free artefact, e.g. the punch, could be explained away as having been produced elsewhere, of iron smelted from a different, low-phosphorus, ore source. However, it is clear that objects were being smithed at Heeten, and that the one other phosphorus-free sample was a semi-finished strip of steel of the sort that comprises the punch, albeit with a much lower carbon content. Admittedly, the sample numbers involved hardly represent statistical significance. Still, the finds do certainly demonstrate that three different alloys were known at Heeten, that is, phosphoric iron (nails and rod), phosphoric steel (nails), and phosphorus-free steel (rod). The possibility must be considered that phosphorus-free iron was somehow being produced, and that an ultrahigh carbon steel object such as the punch could have been smithed on-site.

It may have been the case that a particular ore type was reserved for high quality steelmaking. Although local phosphorus-rich bog ore was the raw material customarily employed by Germanic iron smelters, there is also very low-phosphorus rock iron ore available in the region that could have been chosen in some instances. Low-phosphorus iron ore was exploited more extensively in the Netherlands during the Middle Ages [8]. Moreover if iron containing only a trace amount of phosphorus is desired, it is theoretically possible that this could be produced from high-phosphorus ore through subtle alteration of the furnace atmosphere and slag control during smelting.

The composition of the punch and rod 18-1-20-2 suggests that phosphorus-free metal was chosen for steelmaking. However, it cannot be argued that phosphoric iron was being avoided due to physical impossibility of carburisation. It is perfectly possible to carburise phosphoric iron: phosphorus slows carbon diffusion, but it does not stop it altogether. Experimental work demonstrates that steel with a range of carbon contents, up to and including cast iron, can be produced by the direct reduction of a high phosphorus ore [3]. The phosphoric steel nails from Heeten demonstrate that ancient smiths could succeed in carburising fully formed pieces of phosphoric iron. Nonetheless the Germanic ironsmiths may still have made the choice to select phosphorus-free iron and/or ore for their highest quality steelmaking, perhaps motivated by a non-technological factor, such as, for example, the attribution of greater value to metal from a 'special' source other than the local bog iron ore deposit.

9. Conclusions

The Heeten punch is a tool of ultrahigh carbon steel that was most probably produced in the solid state. The object has been manufactured from thin strips of metal that have been carburised separately and then welded together; if any capacity for liquid production had existed, then it is far more likely that such a small object (1 cm by 6 cm) would have been made as a single piece. The object was most likely manufactured by high temperature carburisation of extensively forged iron strips. Modern perceptions regarding the difficulty of forming objects from high carbon steel clearly differ from those of ironworkers in antiquity, who smithed this material successfully. Ancient smiths may have found that high carbon content actually facilitates fabrication as the final welding can be done at a lower temperature.

It is postulated that the use of ultrahigh carbon steel by Germanic people beyond the Roman *Limes* represents innovation within an independently developing northern European ironworking tradition. There is no cause to assume that it is an example of technological transfer from the more advanced Romans to less sophisticated northern Europeans. As indicated by the Pliny reference given above, the Romans are in fact more likely to have been consumers rather than producers of high quality iron. Notable in this connection is the fact that the slag-pit smelting method continued in use in Germanic lands contemporaneously with slag-tapping technology being used in Romanised regions, despite the close proximity of Romans (in the case of the Netherlands, this just meant other Germanic people living on the other side of the *Limes*) and despite the extensive interaction and cultural exchange that undoubtedly characterised other aspects of Late Roman-Iron Age life. Northern Europeans actually persisted in smelting iron in slag-pit furnaces well into the 7th century AD, when the alternative technology of slag-tapping furnaces started to appear in the Netherlands, Denmark, and northern Germany. It can be argued that ironworking is more deeply rooted in folk craft traditions than might be expected of a technological practice.

The proposed Germanic solid-state method of production of ultrahigh carbon steel achieved a result very similar to later Near and Far Eastern crucible steel. As a liquid-state technology, the great advantage of the Wootz or crucible process was that it could result in relatively large quantities of homogeneous steel. However, the high degree of processing involved meant that its application was limited to expensive, high-status objects such as swords. For the production of ultrahigh carbon steel tools, a direct process is very advantageous. The maker of the Heeten punch has in fact managed to produce a material with the characteristics of modern ultrahigh carbon steel, breaking up the grain boundary cementite network and producing spheroidised carbides. Heat treatment has been skilfully applied to maximise mechanical properties.

The punch and rod 18-1-20-2 are distinguished from the other Heeten artefacts by their lack of phosphorus. This implies conscious selection of materials for specialised production, for example, of a smith's tool, and possibly a much higher capability in the manipulation of iron ore than has previously been recognised.

The Heeten samples can be viewed in the context of the numerous Germanic Roman-Iron Age pit-furnace smelting sites that are seen across northern Europe. It is not unlikely that further examples of ultrahigh carbon steel could be identified elsewhere. The Heeten finds indicate that phosphoric steel and ultrahigh carbon steel can be considered as purposefully utilised products of the ancient bloomery process.

Very few metallographic analyses of Germanic iron artefacts have been published, and so understanding of the proficiency of Germanic smiths is at the present time far from complete. Although the site of Heeten is not identical in every respect to other Germanic iron smelting sites, it is clear from the ore, slag, and metal analyses that a common knowledge and common level of technical skill were present. The Heeten punch suggests that the quality of Germanic ironworking could be finer than what is known from the contemporary Roman world. By the Early Medieval period, northern European smiths were undeniably conspicuous for their application of sophisticated techniques such as that of pattern welding, which represented the height of the blacksmith's craft. That such a high degree of skill as seen in the Heeten punch was invested in a tool intended for everyday use indicates the value of looking beyond the limits of the Roman Empire for evidence of innovation in early ironworking technology.

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References

[1] A.M. Feuerbach, J. Merkel, D.R. Griffiths, An examination of crucible steel in the manufacture of Damascus steel, including evidence from Merv, Turkmenistan, in: T. Rehren, A. Hauptmann, J.D. Muhly (Eds.), Metallurgica Antiqua. Der Anschnitt Beiheft 8, Bochum, 1998, pp. 37–44.

[2] P. Fluzin, Synthèse des Études Métallographiques d'Échantillons de la forge de Ponte di val Gabbia III (Bienno 5th–6thcentury AD), in: L.C. Nørbach (Ed.), Prehistoric and Medieval Direct Iron Smelting in Scandinavia and Europe, University of Aarhus Press, 2003, pp. 139–145.

[3] E.G. Godfrey, The technology of ancient and medieval directly reduced phosphoric iron, Unpublished MPhil/PhD progression report, Department of Archaeological Sciences, University of Bradford, 2001.

[4] B.J. Groenewoudt, M. van Nie, Assessing scale and organisation of Germanic iron production at Heeten (the Netherlands), Journal of European Archaeology 3 (2) (1995) 187–215.

[5] R.B. Heimann, U. Kreher, I. Spazier, G. Wetzel, Mineralogical and chemical investigations of bloomery slags from prehistoric (8th century BC to 4th century AD) iron production sites in upper and Lower Lusatia, Germany, Archaeometry 43 (2) (2001) 227–252.

[6] H. Jöns, Iron production in northern Germany during the Iron Age, in: C. Fabech, J. Ringtved (Eds.), Settlement and Landscape: Proceedings of a Conference in Aarhus, Denmark, Jutland Archaeological Society, 1999, pp. 249–260.

[7] I. Joosten, J.B.H. Jansen, H. Kars, Geochemistry and the past: estimation of the output of a Germanic iron production site in the Netherlands, Journal of Geochemical Exploration 62 (1998) 129–137.

[8] I. Joosten, H. Kars, Early historical iron production in the Netherlands: estimations of the output, in: S.M. Young, A.M. Pollard, P. Budd, R. Ixer (Eds.), Metals in Antiquity (BAR International Series no. 792), 1999, pp. 243–251.

[9] R. Lauwerier, B. Groenewoudt, O. Brinkkemper, F.J. Laarman, Between ritual and economics: animals and plants in a fourth-century native settlement at Heeten, the Netherlands, Berichten van de Rijksdienst voor het Oudheidkundig Bodemonderzoek 43 (1999) 155–198.

[10] M. van Nie, Germanic iron provision in the second half of the third century AD: slag-pit furnaces and iron hoards, in: L.C. Nørbach (Ed.), Early Iron Production—Archaeology, Technology and Experiment (Lejre), 1997, pp. 115–122.

[11] L.C. Nørbach, Ironworking in Denmark: from the Late Bronze Age to the Early Roman Iron Age, Acta Archaeologica 69 (1998) 53–75.

[12] O.D. Sherby, Ultrahigh carbon steels, Damascus steels and Ancient Blacksmiths, Iron & Steel Institute of Japan International 39 (7) (1999) 637–648.

[13] C. Tizzoni, M. Tizzoni, The Late Roman Ironworking Site at Ponte di val Gabbia III, Bienno (Brescia, Italy), in: L.C. Nørbach (Ed.), Prehistoric and Medieval Direct Iron Smelting in Scandinavia and Europe, University of Aarhus Press, 2003, pp. 49–53.

[14] A.D. Verlinde, M. Erdrich, Eine germanische Siedlung der späten Kaiserzeit mit umwehrter Anlage und umfangreicher Eisenindustrie in Heeten, Provinz Overijssel, Niederlande, Germania 76 (2) (1998) 693–719.

[15] D. Wagner, The earliest use of iron in China, in: S.M. Young, A.M. Pollard, P. Budd, R. Ixe (Eds.), Metals in Antiquity (BAR International Series no. 792), 1999, pp. 1–9.

[16] C. Williams, Personal communication regarding commercial steel pack-carburisation experiments at the Wolfson Heat Treatment Centre, Aston University, Birmingham, 2000.