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HYPEREUTECTOID STEEL
IN EARLY MEDIEVAL SWORD PRODUCTION IN EUROPE[1]

Abstract: Hypereutectoid steel is viewed as a material of exceeding quality for the manufacture of swords, providing keen edges and strong bodies to their blades. A significant group of weapons, where such material was used, comprises some swords from the "Ulfberht" family. It is suggested that these specimens were made using crucible steel, a high-carbon material produced in the territories of Central Asia and India. The article presents in short other examples of European swords, where hypereutectoid steel was identified, and discusses different methods for its production known at the time, possibilities in discerning between them, problems with working with such a material, as well as the resulting limitations and shortcomings. The issues are considered from the archaeometallurgical point of view, with archaeological data, material analyzes and experimental studies serving as the background.

Keywords: swords, hypereutectoid steel, Early Middle Ages

Steels achieving excellent mechanical properties (such as strength, hardness, wear resistance etc.) through appropriate heat-treatment, highly suitable for working parts of weapons and tools, can be classified as high-carbon steels with more than 0.6% C. Specific sorts of such steels are hypereutectoid steels, containing more than 0.77% C and comprising (in natural state) pearlite with proeutectoid cementite.

Properly treated hypereutectoid steels are justly viewed as materials of excellent quality for the manufacture of swords, specifically to provide hard and wear-resistant edges and strong bodies to their blades.

The use of hypereutectoid steels in blades of some European early medieval swords has been confirmed by metallographic analyzes. Unsurprisingly, their presence is scarce. As discussed in this paper, high carbon steel could have been manufactured in different processes at the time.

One of these processes was based on making steels in closed crucibles exposed to high temperatures, enabling partial or total liquefaction of the alloy produced. Steels yielded in such a way are (in historical context) called crucible steels and the crucible steel-making process was, at the time, known and employed in Central Asia, India and Sri Lanka. In short, cake- or egg-shaped ingots of high-carbon steel were formed in sealed crucibles, where initially small pieces of iron were gradually carburised. Both pieces of cast iron and materials of organic matter could be utilized as a source of carbon (Fig. 1). Prolonged heating at temperatures above melting points of high-carbon steels caused that the whole metallic charge (or at least a significant part of it) was brought into a liquid state, what secured both high homogeneity and purity of the final product[2].

The idea that some sorts of crucible steel were employed in the manufacture of European early medieval blades (particularly swords bearing the Ulfberht signature) was introduced by A. Williams on the „Metallurgy: A Touch-Stone for Cross-Cultural Interaction" conference, held at the British Museum, London, England in 2005. He developed this concept in several subsequent publications[3].

Metallographic examinations of „Ulfberht" swords conducted by A. Williams (55 specimens in total) allowed him to divide these examples between five technological groups[4]. He found swords categorized under groups I (9 swords – hypereutectoid steels [more than 0.8% C]) and II (5 swords – eutectoid steels [around 0.8% C]) to be clearly distinct from the rest. These weapons were made in part or in whole[5] from steels, which are much higher in carbon content (and lower in slag content), and which, therefore, would have been very

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[2]   Feuerbach 2002, 2, 153-180, here, the process with its possible variations is described in great detail; Williams 2012, 24-48.

[3]   Most recently, Williams 2012, 116186; see also Williams 2007; Williams 2009; cf. Astrup and Martens 2011; Williams 2011.

[4]   Williams 2012, 118.
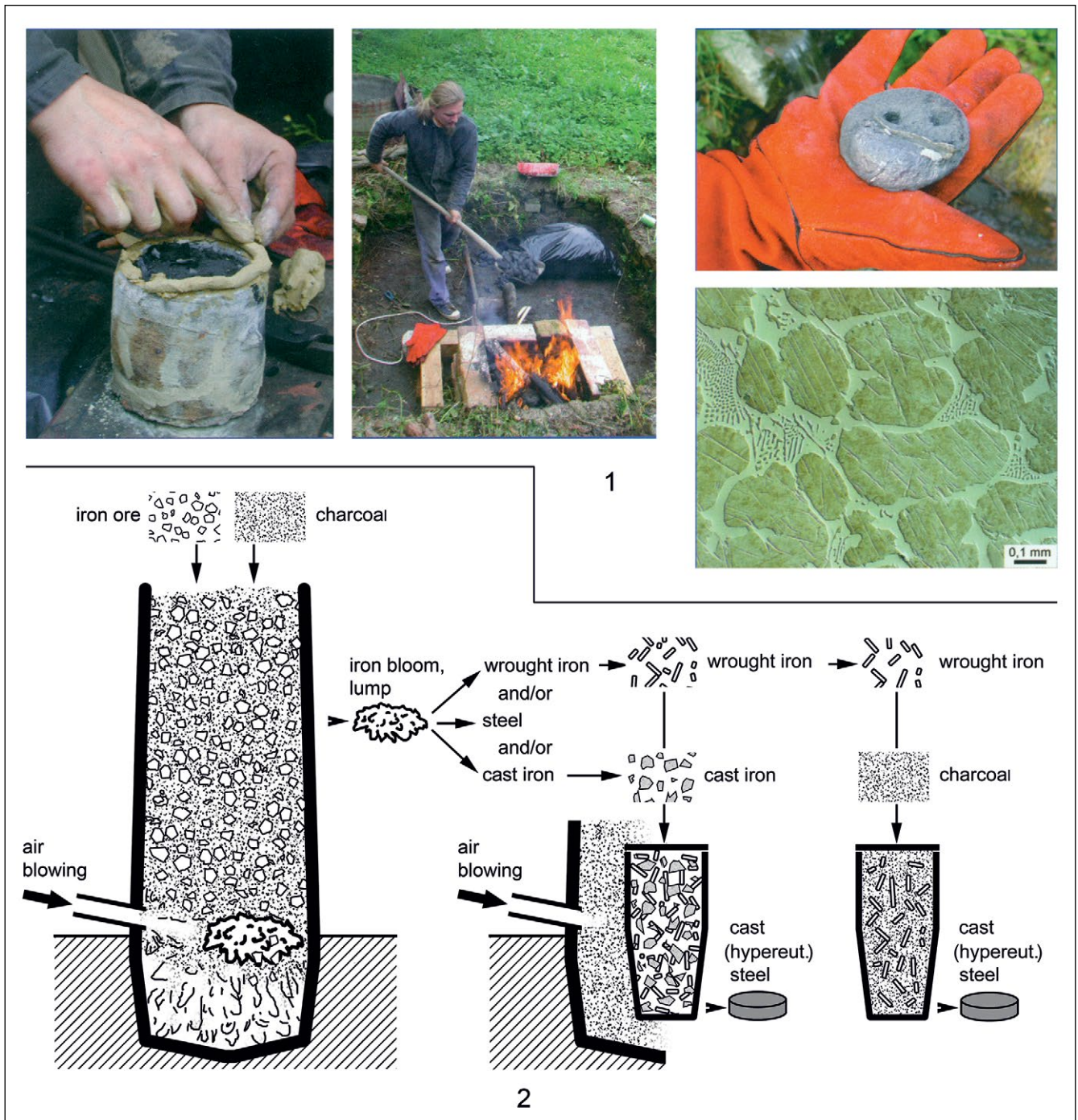
[5]   Cf. Williams 2011.

Fig. 1. Production of steel – the crucible method: 1 – experimental crucible steel production (sealing of a charged crucible, heating the crucible, the ingot [here of cast iron] obtained and its microstructure documented; Fabiánek et al. 2003); 2 – principle of the crucible method (bloomery furnace [on the left] that might have produced both wrought and cast iron; these can be charged into crucibles [on the right], heated and turned within the crucibles into a liquid state; drawing by J. Hošek).

serviceable as swords. All of these examples bore the signature spelled +VLFBERH+T[6]. In addition, no hypereutectoid steels were found in any of the swords with a variant spelling. This lead A. Williams to the conclusion that these were

the „original" Ulfberht blades[7]. Swords from groups I–II all seem to be of a very high quality, and – as he suggests – the raw material used in their manufacture could have been some imported crucible steel.

Since then, a number of other sword blades, where eutectoid–hypereutectoid steels were utilized, has been examined. Some corresponding experiments have been carried out as

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[6] It needs to be underlined that due to poor information on the context of their finds, the dating of these swords cannot be determined too precisely. In addition, although the spelling is coherent in this group, secondary characteristics of the signatures show some variation.

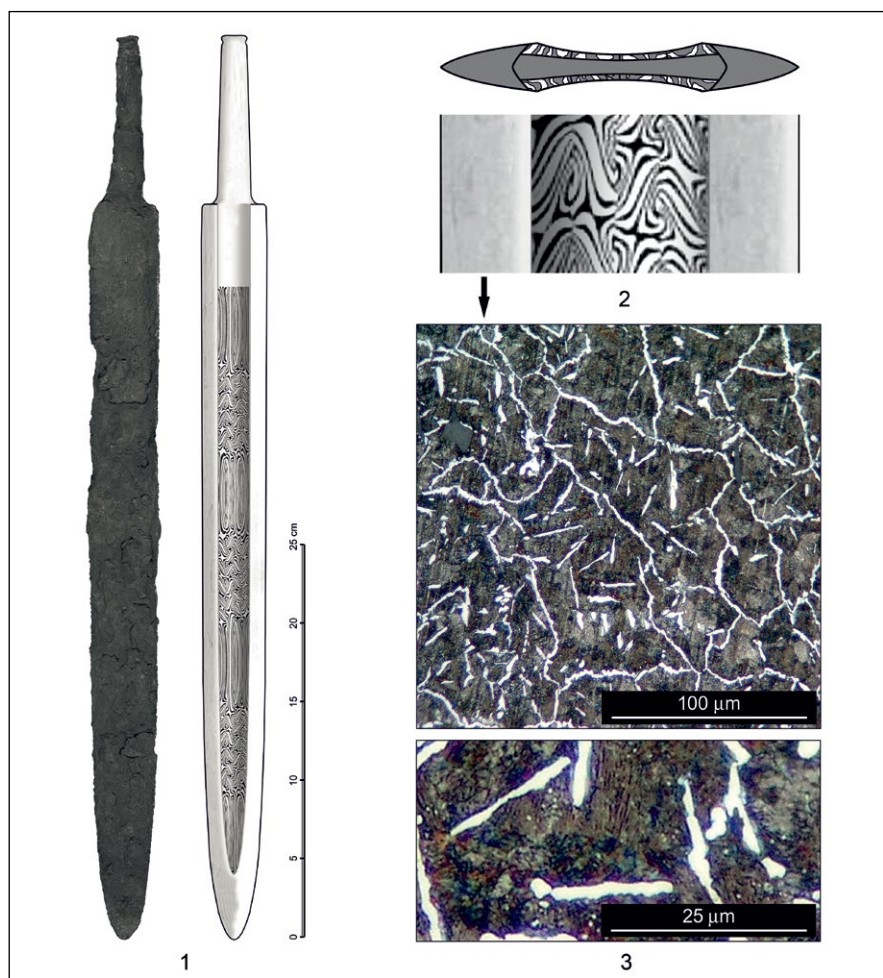[7] Williams 2009, 124-130; Williams 2012, 118-140.

Fig. 2. Example of a sword made of steel reaching hypereutectoid carbon content: 1 – the 9th century sword from Stará Kouřim (Czech Republic), whose cutting edges were in part of their volume a hypereutectoid steel; 2 – schematic cross section and expected appearance of a part of the pattern-welded blade; 3 – hypereutectoid structure documented in the cutting edges, consisting of pearlite and proeutectoid cementite. Photos and drawings by J. Hošek.

well. What follows, is the discussion whether there were truly other means for producing hypereutectoid steel known to and exploited by ironmasters from early medieval Europe.

In order to understand the discussed issue properly, let us have a more detailed look on the metallographical investigation related to the use of hypereutectoid steels in Europe during the first millenium AD. The first group of „Ulfberht swords" (employing hypereutectoid steel), which was introduced by A. Williams, and which is the most important for our discussion, comprises following weapons: a sword from Eura in Finland, now in the Helsinki Kansali Museum[8], a sword from the Oslo Historisk Museum, Norway[9], two swords from the Bergen Historisk Museum in Norway[10], two swords from Elbe River, both deposited in the Museum für Hamburgische Geschichte in Germany[11], a sword from the Deutsche Klingenmuseum in Solingen, Germany[12], a sword from the River Rhine at Karlsruhe, Germany[13], a sword from a private collection[14].

But there are also other swords, contemporary with those from the group I, provided with cutting edges of hypereutectoid steel, and without the Ulfberht signature, or simply without any evidenced inscriptions. One such a sword is a weapon from a 9th century cemetery related to the early medieval stronghold of Stará Kouřim, Czech Republic[15] (Fig. 2). Two other finds come from Russia: a 10th century sword from the cemetery of Gnezdovo[16] that was related to the site of Smolensk, and a 9th–10th century sword from the cemetery of Mihajlovskoe near Âroslavl'[17].

Somewhat earlier swords are those from the Lombard necropolis of Benevento in Italy. Only two blades have been examined, but both of them proved to had been made using hypereutectoid steels[18]. Furthermore, five 3rd–5th centuries swords were identified in the Volga-Kama region in Russia. Two specimens come from 3rd–5th centuries cemeteries of Tûm-Tûm and Ust-Bryskinskij, one sword from a 4th–5th centuries cemetery of Kudaš, and, finally, two examples from a necropolis of Tarasovo[19]. The oldest sword made of hyper-

[8] Williams 2009, 130-134.
[9] Williams 2009, 127.
[10] Williams 2009, 130-132.
[11] Jankuhn 1951, 224; Williams 2012, 122, 125-126.
[12] Williams 2012, 125.
[13] Williams 1977; Williams 2012, 123-124.
[14] Williams 2012, 134.

[15] Hošek and Košta 2013.
[16] In this article the ISO 9:1995 standard has been used for the transliteration.
[17] Kolčin 1953, 17, 133.
[18] La Salvia 1998.
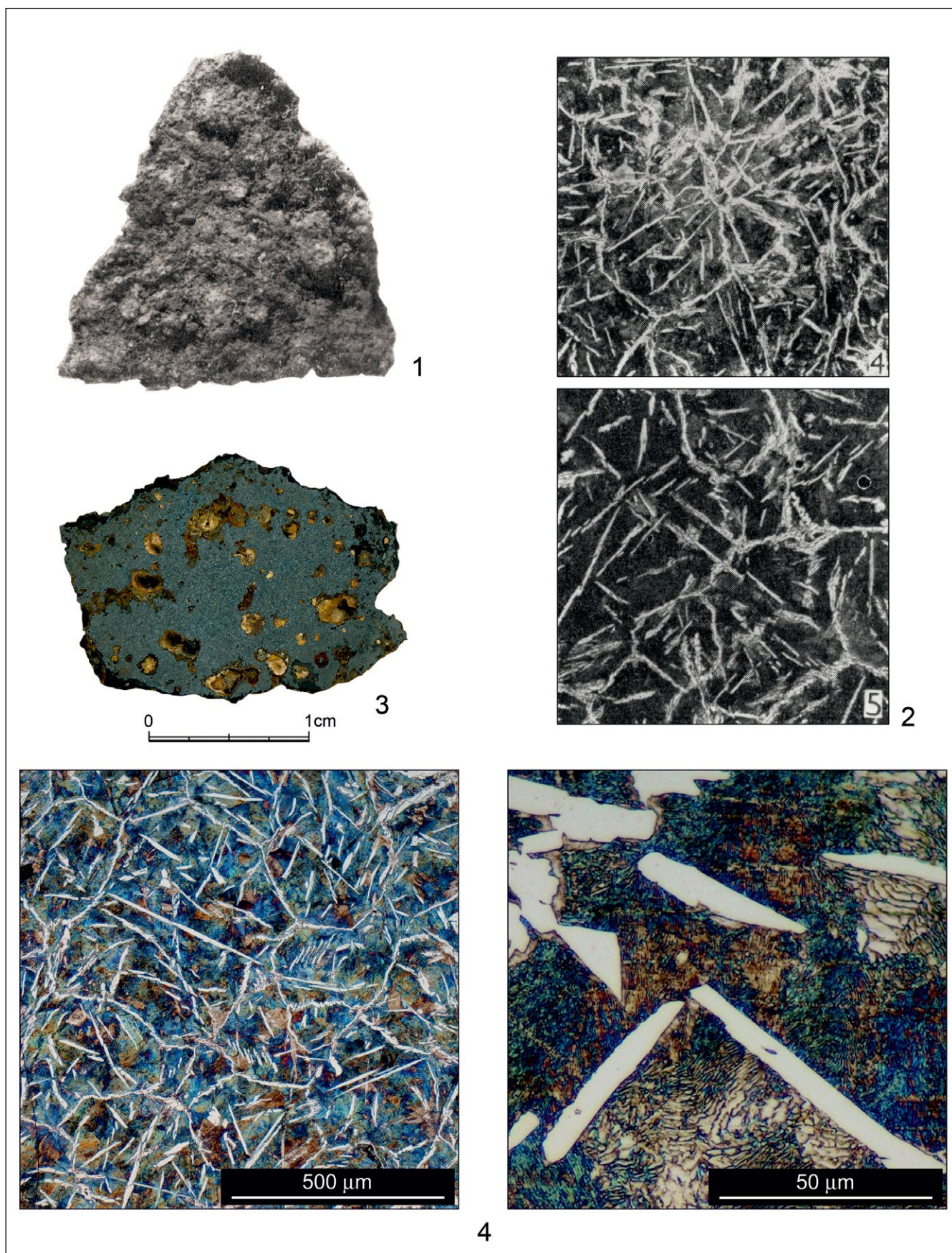[19] Zavâl'ov et al. 2009, 108-109; Goldina and Bernc 2010, 154.

Fig. 3. Example of a carbon-rich lump uncovered during archaeological excavations: 1 –fragment of a lump (here without a scale) coming from the 10th–11th centuries bloomery in Olomučany, Czech Republic; 2 – microstructure of the lump, published by R. Pleiner (Pleiner et al. 1984, 57, T. IV), who interpreted it as a hypoeutectoid steel (this misinterpretation was caused by a mistake in hardness measurement); 3 – macrophotograph of the sample after re-examination (photo by J. Hošek); 4 – new photographs of the microstructure, which show a hypereutectoid steel with approximately 1.4% C. Photos J. Hošek.

eutectoid steel, which can be considered as a European product, comes from a 2nd–3rd centuries necropolis of Lebedevka VI in the South Ural region of Kazachstan[20]. Regarding the dating and provenance of all these finds, one can see that the appearance of swords made entirely or partially of hypereutectoid steels was not restricted to any specific region or period.

No surprise that most of these weapons have been found in a non-hardened (unquenched) condition, as identification of the hypereutectoid steel is easiest when a metallographic structure consists of pearlite and cementite. In fact, the only weapon found in a hardened condition is one of the Langobard swords published by V. La Salvia[21], who employed a chemical analysis to determine the carbon content of the material[22]. Indeed, hypereutectoid steels might have been used in past much more frequently than commonly expected, as identification of hypereutectoid steels is problematic by means of optical metallography when heat-treatment was applied, respectively, when such steels were fully austenitized prior to quenching.

It is also interesting that nearly all of the non-hardened blades have revealed cementite in the form of networks and needles. This suggests that their makers did not apply the techniques most suitable for forging of such materials, which would result in the structure consisting of pearlite with fine particles of cementite scattered throughout. The problem is that both network and needles of cementite decrease the toughness of high carbon steel. Hence, it seems that these manufacturers did not fully understand, what material they were working with, or – in contrary to smiths from areas, where the production of crucible steel has been evidenced[23] – they simply did not master the means for proper treatment of such steels.

All this suggests that hypereutectoid steels were not a material of common use in the European environment, especially when there is no evidence of a routine use of such materials in other sorts of contemporary weapons and tools. Not surprisingly, A. Williams and V. Zav'âlov et al. all view the hypereutectoid steels in swords as a foreign element, whose presence can be (or even should be) explained by an import of raw materials, or even weapons themselves, from places, where the production of crucible steels took place.

While hypereutectoid steels seem to be unusual in medieval Europe, steels with carbon content in the range of 0.6% to eutectoid (i.e., 0.77%) composition were employed in the manufacture of weapons and tools frequently. The second group determined by A. Williams comprises only five swords[24],

but – for instance – detailed metallographic investigations[25] of eight selected swords coming from the 9th–10th centuries stronghold of Mikulčice, Czech Republic, confirmed that at least the cutting edges of swords, quenched and possibly tempered, might have been (at the time) made of eutectoid steel regularly. Five out of the eight investigated Mikulčice blades have revealed eutectoid or nearly eutectoid composition, two others can be still determined as high carbon steels (carbon content varying between circa 0.5 and 0.77%)[26]. In fact, pearlitic or nearly pearlitic structure has been observed (metallographically) in working parts (cutting edges as a rule) of numerous early medieval weapons[27].

Considering the European metallurgy of the 1st millennium AD, the bloomery process was the sole method of the manufacture of iron alloys. Despite the common consensus that the material acquired using this practice was of little carbon content, it was possible – as evidenced by historical examples and modern experiments – to produce steel or even cast iron directly from iron ore, when certain requirements were met (Fig. 3).

While it is rightly presumed that many bloomeries directed their smelting towards obtaining malleable wrought iron, it is highly probable that some individual groups of iron-makers understood the needed conditions for making steeled blooms and were taking advantage of that knowledge[28]. The manufacture of primary steel most probably required an iron ore of a higher grade, favourably with greater than average manganese content[29], charged into the furnace with the fuel in a ratio of at least 1:1, and the burning of the charge supported by a stronger air blow. The forming lump needed to be protected against secondary re-oxidation[30]. The presence of phosphorus, abundant in bog iron ores in the form of vivianite precipitates, could also have played a role in the forming of carbon-rich structures[31].

Surprising easiness of obtaining cast iron in a bloomery furnace was proved by P. Crew[32], which led to the suggestion that cast iron could have been a by-product of

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[20] Zavâl'ov et al. 2009, 108-109.

[21] La Salvia 1998.

[22] Unfortunately V. La Salvia (1998) did not specify the analytical method used.

[23] See, e.g., Feuerbach 2005, 28-29.

[24] The group consists of "Ulfberht swords" that have revealed eutectoid or hypoeutectoid structure of pearlite (and ferrite), i.e.,

the blades were found in an unquenched state in the place (places) of sampling.

[25] The samples were annelaed prior to the examination (in laboratory conditions) in order to change their crystalline structure to a one containing solely pearlite and ferrite (or cementite). This consequently allowed to assess them in terms of both the distribution of components and the carbon content.

[26] Košta and Hošek [in press].

[27] Of course, one must keep in mind that a more rapid cooling, still resulting in pearlite and proeutectoid ferrite or cementite, causes predominate formation of pearlite. Hence, when steel is cooled somewhat more rapidly, both slightly hypo- and hypereutectoid steels may consist only (or predominantly) of pearlite, what would in case of slow cooling suggest the eutectoid (or nearly eutectoid) composition.

[28] Cf. Rehder 1989; Wagner 1990.

[29] Salter 2005; cf. Tylecote 1962, 191.

[30] Pleiner 2006, 137.

[31] Cf. Kędzierski and Stępiński 2006.
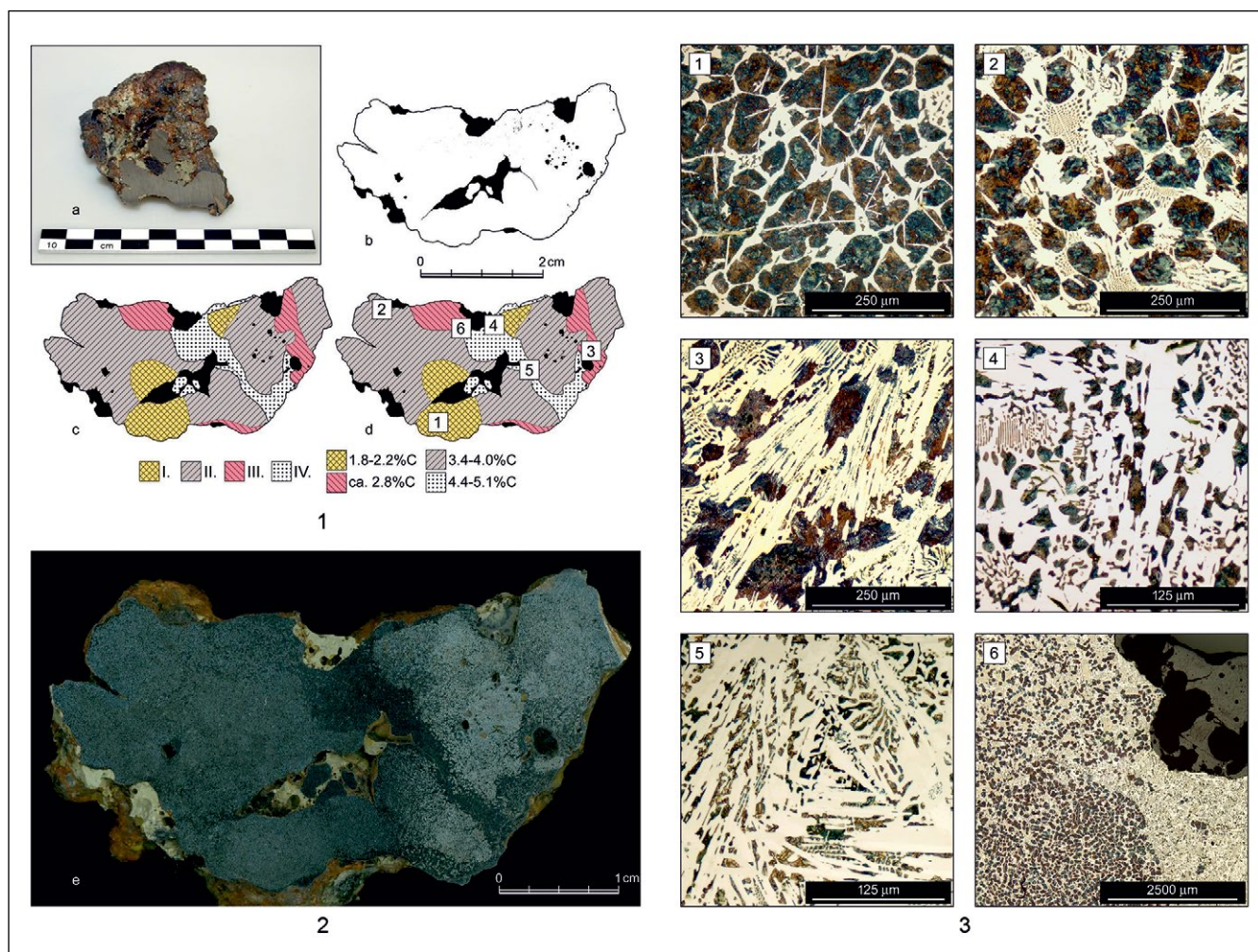
[32] Crew 2004; Crew et al. 2011.

Fig. 4. Example of a carbon-rich lump obtained by the bloomery process: 1 – the piece of an experimentally produced lump submitted for metallography, cross section of the piece with depicted distribution of slag and cavities, and with layout of structures differing from each other in carbon content; 2 – the specimen after etching with Nital (scanned); 3 – the metallographic microstructures observed (varying between hypereutectoid steel and cast iron). Photos and drawings by J. Hošek.

high-carbon steel production rather than simply a random accident. This was full well confirmed during independent experiments (Fig. 4)[33], and corresponds with archaeological finds (Fig. 3)[34].

First suggested by L. Sauder[35], an important step for understanding the mechanism of high-carbon alloy production is the working of the so-called „Aristotle furnace."[36] It was also described in detail by O. Evenstad in his treatise on steel making, first published in 1790[37].

In principle, the accompanying process consists of passing wrought iron through a simple, small, cylindrical or slightly conical shaft of 3 heights to 1 diameter ratio, heated with charcoal fuel (which also serves as the carbon donor) to temperatures sufficient to melt metal chunks introduced into the furnace. Below the oxidizing zone, where the artificial blast enters the shaft[38], carbon avidly diffuses into the liquid or semi-liquid mass, resulting in a rather homogeneous hard steel. Moreover, by changing the parameters of the smelt (most importantly the depth of the carburization zone below the blast hole), it is fairly simple to obtain a material varying between mild steel and cast iron[39] (Fig. 5).

Unsurprisingly – taking into consideration the obviously minimal chance for the occurrence of any tangible remains – it has to be emphasized that there are no archaeological evidences that this method was utilized during the Early Middle Ages in Europe. Even though, the utterance of its sheer simplicity, efficiency and efficacy is extremely telling[40].

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[33] Kucypera 2011; Wrona 2013, 5-10.

[34] Merta and Hošek 2007; Navasaitis and Selskienė 2007.

[35] Sauder 2010.

[36] Aristotle, *Meteorologica* IV: 6.

[37] Evenstad 1790, 437-441; cf. Wagner 1990.

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[38] Data provided from independent experiments allow to conclude that there is no problem whatsoever to reach sufficient temperature levels for the process to proceed using a set of simple, single chamber bellows (Wrona 2013, 5; Hošek et al. 2014).

[39] Sauder 2010; Hošek et al. 2014; Kucypera et al. 2014.

[40] What further complicates the subject, is the possibility of recreating the conditions of this "Aristotle method" during the bloomery process. An experimental study of this phenomenon was carried out with success (Wrona 2013). Whether the melting
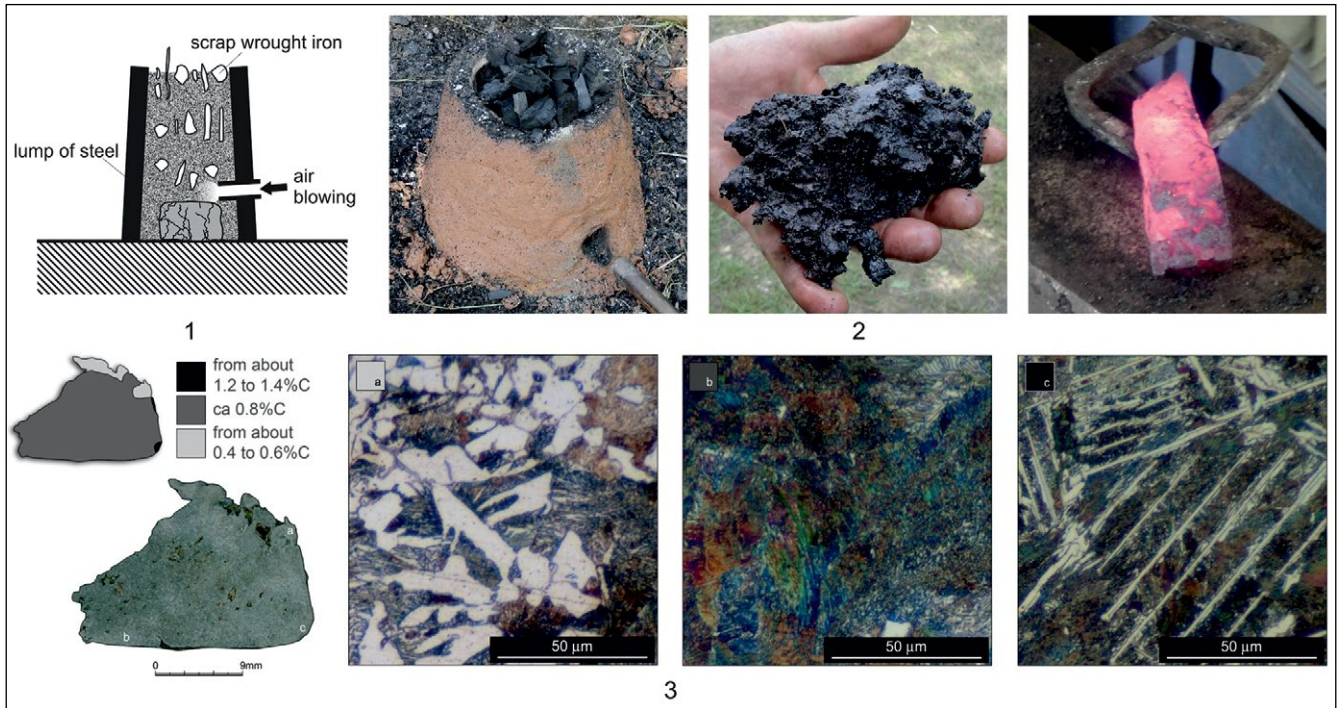
Fig. 5. Production of steel – the "Aristotle method": 1 – principle of the "Aristotle method;" 2 – experimental "Aristotle steel" production (the furnace used, lump of steel yielded and a bar of the steel after some forging); 3 – piece of the lump examined metallographically and the microstructures observed (from the left – hypoeutectoid, eutectoid and hypereutectoid steel). Photos by J. Hošek, P. Kucypera; drawing by P. Kucypera.

HE crucible steel	HE bloomery steel	HE „Aristotle" steel
Relatively homogeneous in macrovolume	Rather heterogeneous in macrovolume	Rather homogeneous in macrovolume
Very little slag inclusions	Slag inclusions more or less present and often rather unevenly distributed within a sample, bigger intrusions can occur	Slag inclusions present in small quantities
Very low concentration of FeO in the slag inclusions (below 4%)	High concentration of FeO in the slag inclusions (up to 70%)	Low concentration of FeO in the slag inclusions (at least 6%)
Ready for use after smelting	Requires heavy compressing/consolidation after smelting	Requires little compressing/consolidation after smelting
Spheroidal cementite possible (effect of low temperature forging)	Spheroidal cementite possible (effect of low temperature forging)	Spheroidal cementite possible (effect of low temperature forging)
Higher silicon and manganese concentration (above 0.05%) in the metal matrix	No to trace concentration of silicon and manganese in the metal matrix	Higher silicon and manganese concentration (above 0.05%) in the metal matrix
Phosphorus present in small concentrations in the metal matrix	Phosphorus present in the metal matrix in variable quantities or not present at all	Phosphorus present in the metal matrix in variable quantities or not present at all

Tab. 1. Material characteristics of different types of high-carbon steels available during the Early Middle Ages in Europe.

The question arises, whether it is possible to distinguish between crucible and bloomery (and „Aristotle") hypereutectoid steels by means of material analyzes. It is generally very difficult to tell these sorts apart. Nevertheless, some criteria could be helpful for the identification of the manufacture technology. They are summarized in Tab. 1[41].

Actual differences in materials obtained by applying the above-described technologies can be much greater. It is, therefore, very hard to properly distinguish between the discussed types of high carbon steels, and the listed features serve as indicators in a far limited way.

Conclusions

It was possible to produce hypereutectoid steel in Early Medieval Europe. This is suggested by numerous smelting experiments as well as archaeological finds. There is a number of sites, where manufacture of iron alloy of a very high carbon content (also cast iron; albeit, in many cases, most probably, produced without intent)

of iron in the bloomery was a necessity or not, this does not change the fact that it was possible to directly obtain a steeled bloom of a high carbon content.

[41] Cf. footnote 40; Feuerbach 2002, 221-227, further literature there.

was identified. There are also sites, where applied smelting installations made it definitely possible to manufacture steel directly.

Hypereutectoid steel is encountered mainly in sword blades, this clearly indicates its special use. With the average quality of iron alloys of the time, this material was of exquisite standard in terms of mechanical properties. In some cases, it was used for forging the whole mass of a blade. Such practice can be justified by the quality (maybe foreignness?) of the steel, its special properties, therefore, a reluctance to „contaminate" it. Different tools and weapons (other than swords) with cutting-edges made of hypereutectoid steels are identified very rarely.

Even though, it is debatable whether European blacksmiths had sufficient knowledge in the ways of processing of high-carbon steels. Properly worked steel should consist of individual cementite particles dispersed in a pearlitic matrix. Cementite needles and laths decrease its toughness.

When forged, it often has a tendency to red short, and its heat-treatment is very difficult – in most cases it was omitted. With the lack of understanding of optimal forging and heat-treating of hypereutectoid steels, a blade made using such materials was in terms of quality similar to a properly quenched blade with sections made of hypoeutectoid steel. The „original Ulfberht" could have been an experiment, lasting for some time, and finally discarded after a range of rather unfruitful trials.

Not all swords, where high-carbon steel was found, were actually made of crucible steel. A large part of hypereutectoid steel swords bears characteristics, which do not allow their straightforward connecting with this technology. In addition, when taking into consideration the „Aristotle" method, it would make it almost impossible to discern between this material and the genuine crucible steel. So, to state that all swords with hypereutectoid steel were made of crucible steels does seem dubious.

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Streszczenie

Stal nadeutektoidalna we wczesnośredniowiecznej produkcji mieczowniczej w Europie

Stal nadeutektoidalna postrzegana jest jako wysokiej klasy materiał do produkcji mieczów, gwarantujący wytrzymałość głowni oraz twardość i odporność jej ostrzy. Istotną grupę militariów wykonanych z użyciem tego surowca stanowi niewielka część mieczy z sygnaturą „Ulfberht". W literaturze pojawiła się sugestia, że egzemplarze te zostały wykute z wykorzystaniem stali tyglowej, wysokowęglowego surowca wytwarzanego na obszarach Azji Centralnej i Indii. W artykule krótko zostały przedstawione inne europejskie miecze, do wykonania których także posłużyła stal nadeutektoidalna, noszące na brzeszczotach inne inskrypcje czy znaki bądź w zupełności ich pozbawione. Omówiono odmienne metody pozyskania tego materiału, możliwości ich rozróżnienia, problemy związane z obróbką stali nadeutektoidalnej oraz wynikające z tego ograniczenia. Rozważania prowadzone były z perspektywy archeometalurgii, w oparciu o znaleziska archeologiczne, analizy materiałowe oraz badania eksperymentalne.