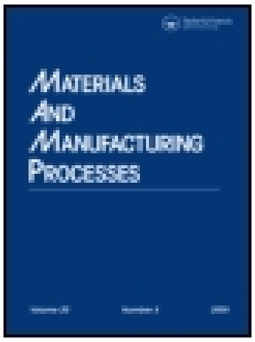


Materials and Manufacturing Processes

ISSN: 1042-6914 (Print) 1532-2475 (Online) Journal homepage: http://www.tandfonline.com/loi/lmmp20

Paper for special issue on “Aspects of Ancient Metallurgy” Roman iron and steel: A review

Janet Lang

To cite this article: Janet Lang (2017): Paper for special issue on “Aspects of Ancient Metallurgy” Roman iron and steel: A review, Materials and Manufacturing Processes, DOI: 10.1080/10426914.2017.1279326

To link to this article: http://dx.doi.org/10.1080/10426914.2017.1279326

MATERIALS AND MANUFACTURING PROCESSES
http://dx.doi.org/10.1080/10426914.2017.1279326

Paper for special issue on “Aspects of Ancient Metallurgy” Roman iron and steel: A review

Janet Lang

British Museum, Scientific Research, London, United Kingdom of Great Britain and Northern Ireland

ABSTRACT
The production of ferrous metal increased during the Roman Late Republican period, Principate and Empire. The direct bloomery process was used to extract the metal from its ores using slag-tapping and slag-pit furnaces. The fuel was charcoal and an air blast was introduced by bellows-operated tuyères. Iron formed as a bloom, often as a spongy mass of metal, which contained impurities from the smelting process, including unreacted ore, fuel, slag and fragments from the furnace walls, while the metal was often inhomogeneous with varied carbon contents. Blooms were either smithed directly into bars or ingots or they were broken up, which also allowed the removal of gross impurities and a selection of pieces with similar properties to be made. These could then be forge-welded together and formed into characteristically shaped ingots. Making steel in the furnace seems to have been achieved: it depended on the ore and the furnace and conditions within it. Surface carburization was also carried out. Iron and steel were used extensively in construction and for tools and weapons. Fire welding was often used to add pieces of steel to make the edges of tools and weapons, which could be heat-treated by quenching to harden them.

ARTICLE HISTORY
Received 25 November 2016
Accepted 3 January 2017

KEYWORDS
Archeometallurgy; bloom; carburization; cast iron; extraction; furnace; ingot; iron; ledeburite; manganese; martensite; metallography; ore; pearlite; quenching; Rome; slag; steel; tools; weapons

Introduction

The Roman period lasted for more than a millennium. Apart from the cultural and political changes that were experienced, a vast number of buildings and other structures were erected during this time. Commerce and trade flourished and the Roman armies tramped across the face of Europe and beyond. All this activity was underpinned, to some extent, by ferrous materials, a fact underlined by Pliny the Elder. In the *Naturalis Historia*, which he completed two years before he died during the eruption of Vesuvius in August 79 BC, he wrote that iron was “a substance which serves the best and worst part of the apparatus for living. Indeed, with iron we plough the earth, plant trees, trim the living vine. We construct buildings, quarry stone, and we use it for every other useful application. But we employ iron as well for war, slaughter, and banditry, not only in hand-to-hand combat, but also on a winged missile, now fired from catapults, now thrown by the arm” [1].

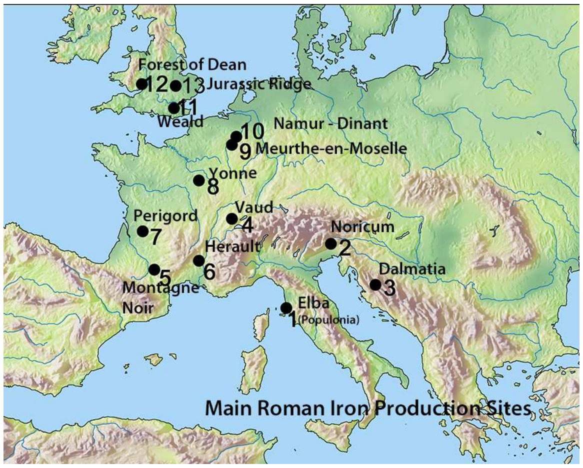
In the 3rd century BC as the Roman state was emerging as a significant political power, iron was being produced throughout Europe (see Map), the Middle East and further afield. As the Roman state expanded, it absorbed and exploited the available resources of production and technical knowledge. Various sources of iron ore were mentioned by Pliny. According to him, iron from some sources was brittle and should be avoided for wheels and nails; others produced iron that rusted readily, while the products of “edging ores” could be used to make sharp edges [2]. He listed important sources: “first place goes to the Seric iron … second place goes to Parthian iron since no other irons are forged from pure metal; all the rest have a softer alloy welded with them. In places such as Noricum (e.g., Carinthia and Styria in Austria) in our part of the world, metal in the vein furnishes this good quality, while in others such as Sulmona it is due to the working, and at others. It is due to the water” [2, 3].

It has been suggested that Seric iron came from China or possibly Sri Lanka [4, 5]. Excellent reviews of aspects of iron and steel in the Roman period have been provided by Giumlia-Mair [6] and Giumlia-Mair and Maddin [7]. They considered the ancient literary sources, the ore resources and their administration as well as the extraction processes. The present paper outlines some of the available evidence relating to ferrous metal use during the Roman period and explores the use and production of steel.

Materials and Methods

Metallography processes using optical and scanning electron microscopy with energy-dispersive X-ray analysis and X-ray diffraction were the main methods used for this research. Archeometallurgical information, gained from examination and analysis of excavated materials, shows that the Romans utilized low carbon or plain iron ($C < 0.1\%$, with slag and oxide inclusions), phosphoric iron (variable compositions, typically 0.5% P or less) and a range of steels, from relatively low carbon (0.25% C) to hypereutectoid (more than 0.8% C). Both grey and white cast iron have been found as by-products of the smelting process. Metallography shows that the compositions were frequently heterogeneous. Ferrous metal production was carried out in bloomery furnaces,

CONTACT Janet Lang j.r.s.lang@btinternet.com Scientific Research, The British Museum, London, WC1B 3DG United Kingdom.
Color versions of one or more figures in the article can be found online at www.tandfonline.com/lmmp.



utilizing the direct process, which is discussed in more detail in a later section of this paper. Forge or fire welding, carburization and quenching were known and practiced, although not always successfully.

The use of metals, especially ferrous metals, expanded during the Roman period. As the quotation from Pliny makes clear [1], iron and iron alloys were used in many practical applications: 1) in construction, for beams, ties, clamps, piles and nails; 2) for a wide range of tools for metal and wood working, agriculture, delicate surgical instruments (unfortunately too corroded for examination), quarrying and stone working and 3) for making armor and weapons. Doubtless the selection of the metal would depend on availability, cost and the experience of the smith. A few examples are given below.

It has been suggested that the Colosseum alone would have required 300 tons of iron for clamps for stone blocks [7]: these would probably be similar to the clamps pins and hoops used in the construction of the Round Temple in the Forum Boarium in Rome, a selection of which has been examined. This building is dated to the 2nd century BC and was refurbished in the Tiberian period [8]. The majority of the fittings sampled were wrought iron but a few (thought to have been part of the refurbishment) contained some areas with up to 0.4% carbon, some of which were martensitic and evidently had been heated, presumably in order to tighten the joins.

Beams were often required in Roman building projects and large lumps of unrefined iron blooms were used to make large beams, such as the one found at Catterick (North Yorkshire, England), which weighed 128 kg [9]. A similar beam (178 kg weight) from Corbridge, Northumberland, England, had been forge-welded from a number of mainly ferritic bloom lumps with some high-carbon areas, applied alternately. The microstructures of these pieces included spheroidized pearlite, pearlitic Widmanstätten structures with grain boundary cementite, and some ferritic areas.

The wooden piles of the Roman bridge over the river Arno at Minturnae, 125 km from Rome, were protected by metal shoes. They were constructed by welding together three or four strips of inhomogeneous ferrous metal together. The metal contained areas of wrought iron and high-carbon steel and had not been quenched [10]. Another 4th century AD Roman pile shoe, consisting of four phosphoric iron bars, was found in the river Maas near Cuijk in the Netherlands [11]. It was presumably made from local ores as bog iron ore contains phosphorus and is not uncommon in northern Europe.

The huge quantity of nails of various sizes, buried at Inchtuthil in Scotland, is well known and clearly indicates the vast number of nails that must have been made throughout the empire. Angus et al. [12] noted that the metal was heterogeneous and the smaller nails had a lower ratio of high-carbon areas to low-carbon areas in comparison with the larger nails and therefore concluded that some selection was taking place, based on the smiths' assessment of the workability of the material.

Some of the earliest Roman ferrous tools, including rings, hooks, nails, clamps, anvils and axe heads, as well as very hard hypereuctoid steel files [13] were found in the 1st century BC *oppidum* of Magdalensberg in the Noricum region. Martensitic steel files [14] were also found on sites at Rauranu (Rom, Deux-Sèvres) and Argentomagus (Saint-Marcel, Indre) in France. By the beginning of the 1st century BC, it appears that iron tools had become straightforward replaceable commodity items: Cato (*On Agriculture* 2) [15] refers to "Iron tools not worth saving". A number of mining tools, including scraper shovels, picks, punches and hammers [16] from the Roman mining site at Rio Tinto, Spain, were dated by radiocarbon from associated wood to between 90 BC and 70 AD. This study of 22 artifacts concluded that the smiths were well aware of how to harden the tools they wanted to harden and that this was achieved either by forge-welding solid-state carburized sheet onto bloomery iron or by case carburizing the bloomery iron surface. All seem to have been cooled rapidly, with 46% quenched to martensite.

Tools found at Vindonissa, Switzerland, a Roman site occupied from the 1st to the 4th centuries AD, appear to have been constructed partly from steel [17]. An axe blade had a steel edge welded on, which had been quenched to martensite (481 HV at the edge). A drill and a gouge were made from several layers: while the outer layers were low-carbon iron, the two inner layers consisted of steel. The edge of the gouge has a maximum 630 HV at the edge. It seems that the layer arrangement may be deliberate [17]. A steel edge was also welded onto the blade of a Roman carpenter's plane, from Vindolanda (Chesterholm, Northumberland, United Kingdom) [18]. A Roman chisel from the same site [19] had a heterogeneous core with some areas of less than 0.15%, but in this case, the edge was carburized (c. 0.8% C) and then slack quenched to martensite (570 HV) (i.e., withdrawing from the quenching liquid allowed the residual heat to temper the edge) so that the structure changed from tempered martensite to upper bainite or radial pearlite, irresolvable pearlite and lamellar pearlite away from the edge.

Steel pyramidal points, used for quarrying porphyry, were found in numbers at the Imperial stone quarries operated at Mons Claudianus in the Eastern Egyptian desert between the 1st and 3rd centuries AD [20]. An examination of one showed a coarse tempered martensitic structure (hardness 476–581 HV; Fig. 1). *Ostraca* found at the site recorded that 36 stonemasons worked at the site, using sledgehammers and iron wedges, as well as adzes and picks or hammers with hard metal

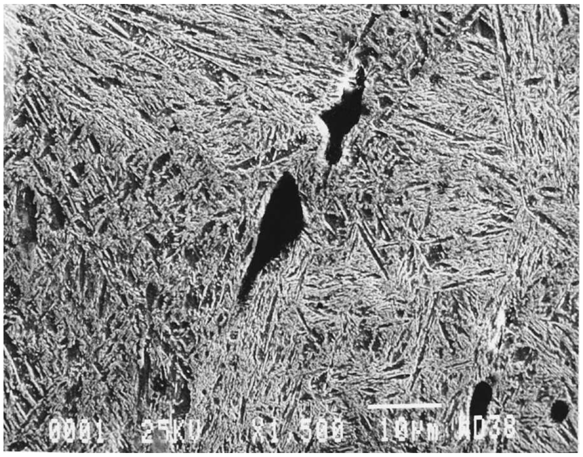


Figure 1. Steel masonry tool tip from Mont Claudianus, 1st to 3rd centuries AD: martensite with glassy slag inclusion.

points. Fresh points had to be refitted every hour. To maintain the equipment, three smiths, one hammer man with six bellows men and hardeners were part of a crew of 49, which is recorded as operating in one of the quarries [21].

The Roman soldier was equipped with armor, a helmet, a shield, a sword, possibly a dagger, spears (*pilae*) and hobnailed boots as well as various tools. It has been estimated that a Roman legion required 38 tons of iron to equip it [22]. The activities of the Roman army and its workshops included making and repairing armor and also an oversight of or direct involvement in metal production. In Britain, for example, the *Classis Britannica* was closely involved in the iron-making activities in the Weald [23] and it has been suggested that the *Legio II Augusta* oversaw iron extraction in south Wales [24]. The workshops varied from the generalized and specialist *fabricae* operated by the army and civil service to smaller, localized producers [7, 25]. *Immunes* were soldiers with specialized occupations who were excused normal duties and included *gladiatores* and *scutarii*, probably swordsmiths and shield makers (Bishop and Coulston 2006, 236).

Bishop and Coulson [25] have summarized the history and workings of the *fabricae*: initially, in the Republic, manufacture was largely carried out by civilian contractors, based in cities; during the Principate, in the north the military tended to set up their own *fabricae* outside the Mediterranean (the operations in the English Weald are an example), but the armies in the east utilized the well-established metal-working traditions in the cities, and from the late 3rd century, mass production for much of the army was centered on major cities and legionary fortresses. A study of 40 fragments of Roman ferrous armor (mail, *loricae*, helmets) from Britain, Denmark and Germany [26] showed that only 10% contained steel, apart from the mail, a third of which were made of steel and showed the highest average hardness (300 HV).

Some projectile weapons reported seem to have hardened surfaces, either by working or by carburizing, and softer interiors. Two *pila* (spears) were dissimilar in composition and construction. One *pilum* from Vindonissa [17] was mainly ferritic with a cold-worked tip while another had a layered ferritic iron and steel structure (maximum hardness 218 HV). The relatively soft shanks of these weapons would bend easily, making their removal from shields difficult, as described by Caesar [27]. Arrowheads found at Uxellodunum, the site of the last battle of Caesar's Gallic campaign, show some evidence of surface carburization and hardening by quenching (possibly not always deliberately), which would have aided penetration. The edges of a square-sectioned catapult bolt had been strongly carburized and quenched to martensite and bainite for maximum penetration [28].

Three 1st century AD *gladii* investigated metallographically [29] were made of steel. Their cores were pearlitic and their cutting edges were quenched to martensite and were extremely hard (HV 500–750) (Fig. 2). Two were made from a single strip of steel, while the third was constructed from two higher carbon layers with a lower carbon layer between them. In contrast, a 1st century AD gladius from Vindonissa consisted of a layer of phosphoric iron (108 HV), sandwiched between two steel layers (0.4–0.6% C) and had probably been slack-quenched to tempered martensite at the cutting edge (216 HV) [30]. The blade of another 1st century AD *gladius*, from Bonn, with steel edges (0.7% C) and a mild steel core (0.3% C), had not been quenched [31]. Three slightly later 1st or early 2nd century AD swords were made of unhardened low-carbon iron [29]. Some later swords have sandwich constructions with steel cores [29, 32], while others were pattern-welded, with steel edges incorporating strips (sometimes twisted) of phosphoric iron, which provided a visual contrast when etched [32, 33]. Two *spathae* from Kent, for example, have pattern-welded cores and slack-quenched martensitic steel edges [34]. Some of a group of 1st century AD daggers had steel cutting edges (Fig. 3) welded on and hardened, while others were low-carbon iron [35].

From the 8th century BC onward, iron was being produced in Europe, and by the second half of the 1st millennium BC, there was extensive metallurgical exploitation of the large iron resources of Elba and on the adjacent Italian coast at Populonia and the Baratti bay by the Etruscans, [36]. This continued after Rome conquered the Etruscans toward the end of the 3rd century BC.

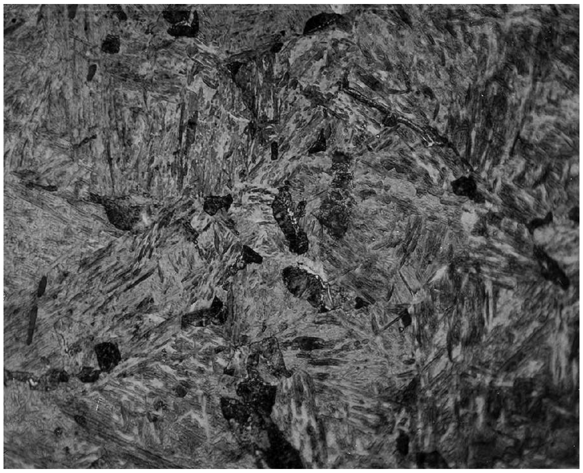


Figure 2. Structure near the tip of the 1st century AD *gladius* found in the river Thames at Fulham, London (British Museum 1883,0407.1), showing martensite with some areas of irresolvable pearlite (width of field 0.27 mm).

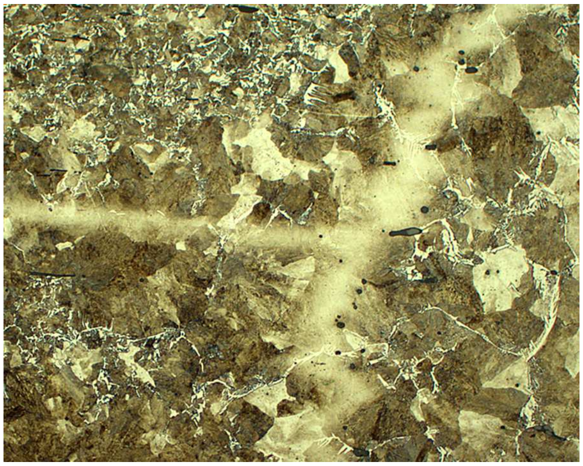


Figure 3. 1st century AD Roman dagger V6/1007, showing a fire-welded join between the core (right, larger grains) and the cutting edge section, which has a weld down the middle and smaller grains (left).

Diodorus of Sicily (ca. 60–38 BC) described the iron industry on Elba and the nearby coast [37], saying that the island had "much iron rock which they quarry for [s]melting the men working the ore pound the rock and burn the broken stones in cleverly designed furnaces. Then smelting the stones by means of a great fire in these furnaces, they cut the product into moderately sized pieces resembling large sponges in appearance. Merchants, buying and bartering these objects, transport them to Dicaearcheia (Pozzuoli on the Bay of Naples) and other commercial centers where certain men purchase these cargoes and having gathered together a large group of metal workers, do further work to produce all sorts of objects from the iron. Some are fashioned into types of armour, others are cleverly worked into shapes well suited for double-pronged forks, sickles and other such tools these are then distributed by the merchants to every region."

All the slag remains found on Elba exhibit flow structures indicating the use of tapping furnaces [36]. On the basis of tap holes or runners and tuyères of about 12 cm internal diameter found in different locations on the Baratti plain, Benvenuti et al. [38] proposed that low shaft slag-tapping furnaces with shaft diameters of 40 cm or less were in common use here. The quantities of slag found at the bay of Baratti have been estimated to be 1,250,000 tons or more, although most was removed for re-smelting in the 20th century. Voss [39] calculated the annual production to be in the order of 1,000 tons a year, but Crew [40] has suggested just over a ton: the truth will lie between these extremes. The demands for charcoal for the furnaces were extensive. It seems that there was a shortage of trees on Elba so that the Etruscans were obliged to transfer their smelting activities to Populonia on the mainland. Calculations by Crew [41] have suggested that 116 tonnes of wood and 1776 kg of ore were required to make 156 kg of iron, while Cleere [23, 42, 43] estimated that between 120 and 140 AD, the six iron production sites in the Weald (United Kingdom) produced 66,000 tons of iron, requiring the felling of 15 km^2 of forest. These figures suggest the necessity of managing the resources where large-scale extraction was in progress, perhaps a reason for the involvement of the Roman army in production in some areas.

The principal ores used in the Roman iron industry were iron oxides (hematite, goethite, limonite, magnetite), carbonates (siderite) and, less commonly, weathered hydrated silicates and sulfide ores [44]. The ore was broken up, then roasted to remove water and carbon dioxide and to increase permeability. The particle size produced would be somewhere between 5 and 20 mm in diameter. This preparation was often carried out near the ore source [45], although the furnaces were not necessarily in the same location. Roasted ore is found at smelting sites, but the roasting sites themselves may be more difficult to identify. During the smelting process, the fragmented ore was reduced and metallic iron formed, sometimes as a skin on the surface of the ore particles, [46] and agglomerated in the hottest part of the furnace near the tuyères. At a temperature between 1100°C and 1300°C, molten slag was produced from the gangue (mainly silica, lime and alumina), which drained to the bottom of the furnace with unreduced iron oxide. It was removed either by tapping, while liquid, or as a solid block when the furnace cooled, depending on the design of the furnace.

Based on the method of slag removal, there were two main types: (i) the slag-pit type of furnace was the most widely used outside the Roman world according to Pleiner [46], while (ii) slag-tapping furnaces seem to have been preferred within the frontiers. The capacity of the slag-tapping furnace would be less restricted by slag accumulating at the bottom of the furnace, which would allow the production of large blooms [47]. It has also been suggested that this type of furnace was better for smelting less-rich ores [48]. The large furnaces at Semlach-Eisener in the vicinity of Hüttenberg, in the Roman province of Noricum (see Map), were slag-tapping furnaces well known for producing high-quality iron and steel. The shafts no longer exist. The lower parts were sunken below the level with a pit in front, for tapping the slag and removing the blooms [46]. Ferrous metal was produced at the site from the 1st century BC until the 4th century AD.

The site at Les Martys, Montaigne Noir, near Carcassonne, France, operated large shaft furnaces in the second half of the 1st century BC [49]. A third type has also been identified: the domed or cupola furnace. Dating to the 6th to 4th centuries BC [50], these furnaces were used in the Swabian mountains, south of Stuttgart, and appear to be the earliest form of the large furnaces with domed chambers surmounted with a stack, which operated from before the Roman occupation (200 BC) at Clèrimois (Yonne, France) [51]. Similarly configured furnaces were found at Laxton in Northampton, England [52], which produced an estimated 10,000 tons of slag. These furnaces, together with a change from slag-pit to slag-tapping furnaces, contributed to increased production in Britain after the conquest [53, 54, 55].

Slags are the most obvious product of early iron smelting, as they are usually left near the furnaces, but because the extraction process is a solid-state reaction, some slag particles remain in the bloom with the other impurities. Slags have been extensively studied and provide information on the ores and the processes used in the operation [55–58]. They mainly consisted of fayalite ($2FeO \cdot SiO2$), with wüstite and a glassy matrix containing small quantities of other oxides. The glassy silicates contained very variable amounts of the oxides of aluminum, sodium, magnesium, silicon, calcium, potassium, manganese, titanium, iron, barium, phosphorus, arsenic and sulfur. Depending on the ore, there might be traces of metals such as cobalt, nickel, vanadium, tungsten and even copper, lead or tin. Arsenic, nickel, cobalt, vanadium and phosphorus might partition into the metal. Analyses of the phosphorus and manganese oxide contents indicate if the ore contained significant quantities of these elements. Differences in the Al_2O_3/SiO_2 ratios may suggest different production regimes. Pagès et al. [59] were able to distinguish the use of at least six different reducing systems in their study of bars from Roman wrecks in the Bouches du Rhône (discussed further below). Data from the analysis of furnace bottoms (slag cakes) can be used to estimate the weight of the bar produced, if considered with the data from smelting and smithing experiments [54, 60, 61].

Results and Discussions

Diodorus [37] remarked that the blooms from Elba were partially cut up and resembled large sponges in appearance, which suggests that they had not been consolidated before they were transported and sold. Sometimes blooms or bloom fragments were used for anvils or beams without being transformed into ingots or other semi-products [62]. A Roman iron beam found at Catterick Bridge Yorkshire [63] was constructed from bloom fragments. Many small items such as tools may have been made directly from bloom metal fragments.

In most cases, before the metal could be used, the entrapped slag, sometimes with fragments of fuel, furnace lining or ores [64], had to be removed from the spongy mass of the bloom and the metal consolidated and any cavities eliminated, and there is evidence that blooms were often cut up [64]. A study of 24 blooms (weighing between 2 and 38 kg) by Fluzin et al. [64, 65] confirmed "their intrinsic heterogeneity (numerous slag inclusions and porosities, high variability in carbon distribution (from 0.02% to 0.9% C) and sometimes producing localised inclusions of cast iron)". Some blooms were very homogeneous, consisting of ferrite and low-carbon steel, and were easily forgeable [65]. A Roman period bloom from Nanny's Croft, Arundel, Sussex, and a partially forged bloom found at a site operated by the *Classis Britannica* at Cranbrook, Kent, United Kingdom, in the 2nd century AD [66, 67] showed quench products (martensite) and areas of high carbon of up to 1.5%.

These blooms might have been quenched in order to speed up the cooling process and the thermal shock helped break them up, making the removal of nonmetallic impurities easier. Metallic fragments with different compositions could be differentiated and selected on the basis of color, texture, weight, by response to heating, cutting (while hot), hammering and also touch, taste even and sound (when struck or dropped). Once fragments with the desired properties had been selected, they could be fire-welded together (forging at about 1250°C) to make a trade bar or slab, or fabricated directly to make an artifact. The banding or weld lines that may also result from welding up cavities during the consolidation of the bloom itself can often be observed in micrographic sections.

Sometimes smithing was carried out close to the furnace. There is evidence of on-site bloom smithing at Lercoul, a 3rd century AD site in the French Pyrenees, for example, where twin slag-tapping shaft furnaces produced 400 tons of slag [68]. Bloom smithing hearths have also been identified in close proximity to the Norican furnaces at Semlach/Eisner [69]. At the Piani d'Erna site in Lombardy operated in the 1st century AD, about 500 m from the mine, the blooms were smithed immediately after removal from the bell-shaped tapping furnaces, the remains of which were used to heat the blooms during smithing [70]. The two blooms found on the site were of good quality. The site at Ouiches (central France) operated from the late 2nd to 4th century AD. [71]. It used local ore and in this site the complete *chaîne opératoire* from ore to artifact could be reconstructed. Ouiches may also have supplied the nearby *fabrica* at *Argentomagus,* mentioned in the *Notitia Dignitatum* (end of 4th to early 5th century AD).

The presence of iron bars or other semi-products in urban areas and *oppida* suggests that there was a trading network, which includes all the products of the *chaîne opératoire* [72]. These semi-products included bi-pyramidal ingots, which appear to be compacted blooms or part blooms with ends that have been drawn out to demonstrate their forging properties [73]. Iron in the form of bars (often referred to as "currency bars"), sometimes with pinched ends, has been found in late Iron Age contexts and this convenient tradition continued [74]. Steel bars were found at the 1st century AD trading and iron production site of Magdalensberg (Austria), together with an ingot that appeared to consist mainly of hypereutectoid steel [75]. Hypereutectoid *Doppelstachel* (double-pointed objects) of uncertain practical function were also found on the site [76]. These had been quenched to martensite (900 HV at the tips) and were probably also trade bars [76, 77].

Magdalensberg is known to have been an exporter of iron, probably through the Roman port of Aquileia, as indicated by inscriptions found on the walls in the merchant quarter [78]. An illustration of a Roman merchant can be seen in the Augst Roman Museum [79]. He is portrayed on his tombstone with a selection of his wares, some arranged on a balance. A mosaic from Hadrumetum, Sousse, shows bars being carried ashore from a boat and weighed (C. 250 AD) [79]. Wrecks have provided a number of finds of bars and ingots. One of the two ingots from a wreck off Bonifacio on the Corsican coast was found to be ferritic when sampled, while the other, a slab, stamped SATVRIN (VS), was pearlitic with grain boundary cementite (0.9% C) [80]. Two ingots from a vessel excavated off Rhizon (modern Risan), Montenegro (Fig. 1), were found to be hypereutectoid steel (Fig. 2) with areas of ledeburite and slag (Fig. 3) [81]. One of the most spectacular and significant ferrous metal finds consists of around 500 tons of iron bars, which were reclaimed from 11 Roman wrecks from the mouth of the river Rhône Bouches du Rhône dating between 27 BC and 96 AD [59]. The study of these iron bars has provided important information about the production of iron in the early Roman empire and has illuminated Pliny's comments on iron [2], demonstrating that the Romans were well aware that iron came from different sources, which provided iron with different properties [4, 5]. The bars from the Bouches du Rhône were grouped into different sizes; within each group, the compositions (e.g., carbon content) were fairly consistent, including one group that appeared to be mainly bars of phosphoric iron.

Pagès' study [59] makes it clear that (1) iron, steel and phosphoric iron were recognized and therefore (2) their properties were also recognized (in broad terms), (3) an extensive trade in ferrous metal was being carried out, (4) some standards appear to have been accepted, so that a bar might be purchased for a particular application (the edge of a tool blade, for example), (5) the cleanliness of a high standard, (6) the longer bars were all constructed from two or three separate pieces of metal of the appropriate composition (e.g., phosphoric iron) and many of the welds in these bars were of an exceptionally high standard [82], and (7) slag analyses showed that the metal used to make the composite (mainly longer) bars was (a) not necessarily made of ore from the same mine or (b) smelted at the same site or (c) made by the same production process.

The Bouches du Rhône study has confirmed that a sophisticated organization ensured the operation of the Roman iron and steel industry. Smelted blooms were evidently cut up or broken apart (probably assisted by quenching) and the required material selected and then, it appears, sent elsewhere to specialist workshops to be forged into bars of characteristic dimensions. This division of production into a series of operations, not necessarily carried out in the same location, has been recognized in other specialist activities, such as the making of amphorae. There might be political or economic reasons for this, but the great expansion of the ferrous metal industry at the time would probably have encouraged the rise of specialist production units. When the Romans took over the exploitation of the iron mines at Mt Trgovi, Pannonia, smelting and some forging took place at the site, but the blooms and bars were sent to Siscia (today's Sisak, in Croatia), the seat of the Directorate of the Mines of Dalmatia and Pannonia, for fabrication or distribution [83].

Elsewhere there is evidence of sophisticated iron forging activities in the *oppida* of the northern Paris basin (France) during the late Iron Age [84], including making ferrous metal sword blades, sheet for scabbards and steel was also used and worked. Noricum (Carinthia, Austria) was noted for the quality of its iron and the production of steel [2] and was annexed by Rome about 15 BC. The *oppidum* of Magdalensberg in Noricum was the trading center. Pannonia (an area that produced three million tons of iron slag by the end of the 4th century AD) was forcibly annexed about 10 years later.

Pliny wrote that the products of "edging ores" could be used to make sharp edges [2]. "The product of edging ores" may reasonably be interpreted as steel, but there is little to explain how it was made, although archeology makes clear that it was extensively available without having to have extensive recourse to distant sources.

There were probably a number of ways in which steel could have been made.

1. When the inhomogeneous blooms were broken up for smithing, either by cutting or by quenching, steely pieces of metal could be selected for use directly or agglomerated by welding them together. A piece of steel could be welded onto a lower-carbon core to make an edge: a plane blade from Vindolanda is an example [18]. Usually the joins can be distinguished by an abrupt change in composition and morphology (Fig. 3), and sometimes a line of inclusions marks the join.
2. Iron could be case carburized by heating it in a hearth, crucible or furnace in the presence of a carburizing material: evidence of case hardening using organic wastes, horns and bones was found at several of the North Paris Basin forges at Bobigny "La Vache à l'Aise", Acy-Romance and Condé-sur-Suppé [84]. Here the transition zone is usually less marked than in (1).
3. Steel could be made by reducing cast iron. The evidence from Ponte di Val Gabbio [85] indicates that the indirect process may have been initiated there in the 4th to 5th centuries AD. Mack et al. [86] have discussed a process they suggested was used to make good-quality steel at Saxon Hamwic (Southampton), England. Crew [87] commented that there were sufficient examples to suggest that the production and use of cast iron (and high-carbon steel) were not as unusual as had been previously thought [88–92].
4. Crucible steel was made in the Indian subcontinent from the beginning of the first millennium AD, either by in situ carburization of wrought iron with carboniferous materials in a crucible or by heating wrought iron together with cast iron in a crucible (co-fusion) [93]. Steelmaking crucibles do not seem to have been recorded in the archeological record, however, although the small "Aristotle" type of furnace used experimentally by Sauder might be overlooked [94].
5. Steel blooms could have been produced intentionally in the smelting furnace. Excavations have discovered a number of steel blooms, ingots and semi-products (Figs. 4, 5 and 6). The quantities that have been found suggest that high-carbon steel was being made in the furnaces by the direct process. Norican steel was well known and prized, and the presence of manganese in the ore has been considered by some to be the main factor in the production of steel.

Steelmaking has been discussed [95–97] also in relation to producing cast iron in a bloomery furnace [87]. Apart from the presence of manganese, other factors in the production of steel are the ore to fuel ratio and the blowing rate, which consequently affects the temperature in the furnace. Experimental smelts by [98] used a higher blowing rate and found

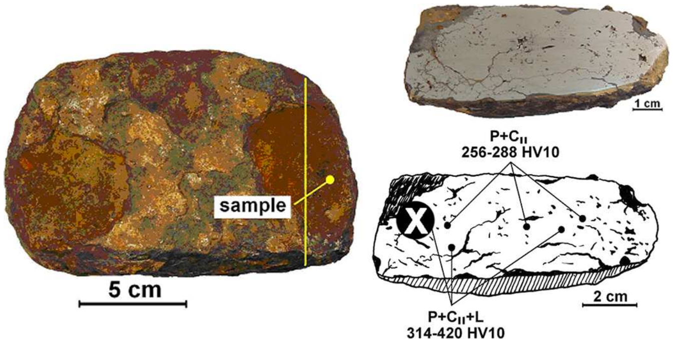


Figure 4. Ingot excavated from a 1st century AD Roman vessel at Rhizon (modern Risan, Montenegro) by the Antiquity of Southeastern Europe Research Centre, University of Warsaw: left, ingot with sample section indicated; upper right, polished section; lower right, diagram showing the main features and hardness values. Reproduced by kind permission of M. Biborski and J. Stępiński.

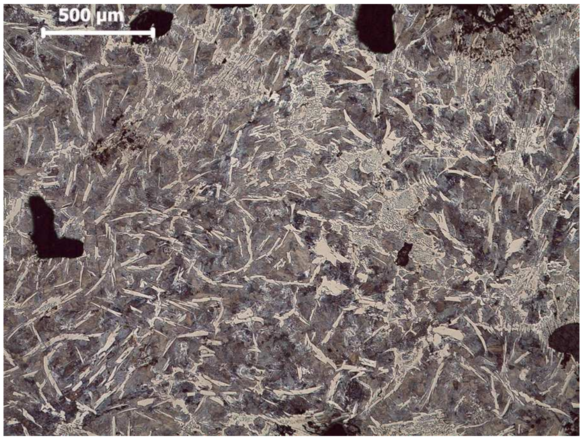


Figure 5. Rhizon steel ingot: microsection at X in Fig. 4, at low magnification, showing pearlite and ledeburite with slag inclusions. Reproduced by kind permission of M. Biborski and J. Stępiński.

that recharging the furnace several times with tapped and broken up slag and charcoal met with some success. Pleiner demonstrated that it was possible to produce a steel bloom apparently without a manganese-rich ore [99]. He used an underground furnace designed so that a carburized bloom could be maneuvered to avoid being decarburized by the air blast or at the mouth of the furnace. Truffaut [97] has suggested that if a manganese-rich ore is used, the manganese is reduced in the upper part of a bloomery furnace, which facilitates the carburization of the iron. Iron, manganese and carbon are all open to reoxidation in the combustion (reoxidation) zone, where a manganese-rich cast iron can lose all its manganese (as MnO), a part of the carbon (CO) and a little iron (FeO). The oxides pass into the slag or escape as gas. Manganese is more sensitive to oxidation than carbon. In this process, cast iron is formed in the upper part of the bloomery furnace and is then refined to steel at the air duct, by a selective reoxidation of the manganese. This suggests that manganese effectively protects the carbon and iron from oxidation (and therefore loss). This was born out by Crew's experimental smelts (XP92 and XP93) using ores with more and less manganese: this produced cast iron in the first case and low-carbon iron in the second [87]. The question of how the Roman smelters managed to control the decarburization of a carbon-rich bloom in the bloomery furnace is not entirely understood: it seems that it was possible, but the methods are not yet completely clear.

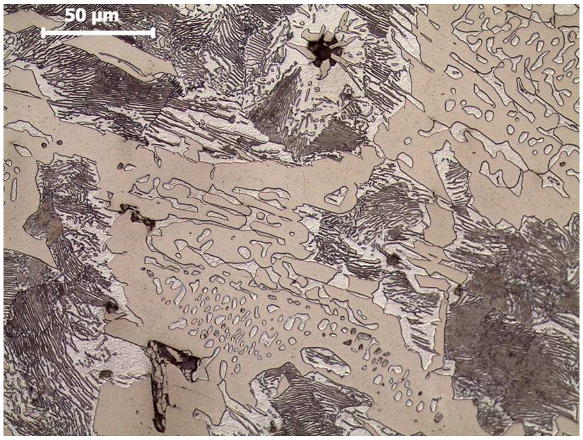


Figure 6. Rhizon steel ingot: microsection at X in Fig. 4, at higher magnification, showing pearlite and ledeburite with slag inclusions. Reproduced by kind permission of M. Biborski and J. Stępiński. Map: iron working sites during the Roman period (after Pleiner, 2000, fig.12).

Conclusions

Roman iron was produced by the direct (bloomery) process and as a result was frequently inhomogeneous with segregation and banding. The bloom metal varied from wrought iron, low-carbon iron and phosphoric iron to hypo- and hypereutectoid steels and cast iron. Materials selection appears to have been pragmatic and appropriate. Pieces were fire-welded together where necessary: decarburized zones, oxide and slag inclusion bands, and changes in composition or morphology identify the welds. Some edges were carburized; others were hardened by incorporating steel strips by forge welding, which were then forged or ground. Heat treatment was variable both in application and in effectiveness. Tools and weapons with steel (carbon-rich) edges were often quenched to martensite. This was tempered, probably by auto-quenching. Even objects with lower carbon contents were frequently cooled rapidly. The bars from the Bouches du Rhône and the *ostraca* from Mons Claudianus are just two indications of the organization underpinning the Roman ferrous metal industry.

With regard to steel, it has almost been 20 years since Chris Salter [100] suggested that high-carbon steels were being selected and used in the late Iron Age and in the Roman and early medieval periods. For archeologists and some archeometallurgists, this was a surprising concept. In 1981, Cleere wrote that "the metallographic examination of artefacts seems to argue against deliberate and consistent direct steel production" [101]. Since then, an increasing amount of evidence has been accumulating from excavations, from metallographic and analytical studies, and from experimental smelting and smithing, to show that steel with various carbon contents was being deliberately selected and used. It now seems clear that steel was being made intentionally and investigations continue to understand more about its manufacture in the bloomery process before the indirect steelmaking process became established.

Acknowledgments

The author would like to thank Dr. M. Biborski and Dr. J. Stępiński, both of Krakov, for their kind permission to use their metallographs. The author would also like to thank Dr. J. Stępiński for encouragement and invaluable advice.

References

[1] Pliny the Elder. *Naturalis Historia*, 34, 138–139. In *Greek and Roman Technology: A Sourcebook*; Humphrey, J.W., Oleson, J.P.; Sherwood, A.N. Trans.: Routledge: London/New York, **1998**; 593–594.

[2] Pliny the Elder. *Naturalis Historia*, 34, 143–146. In Rackam, H. Trans., Loeb Classical Library 934, Harvard University Press: Cambridge, MA, **1999**; 138–139.

[3] Pliny the Elder. *Naturalis Historia,* 34, 143–146. In Rackam, H. Trans., Loeb Classical Library 934; Harvard University Press: Cambridge, MA, **1999**; 134–136.

[4] Giumlia-Mair, A.; Maddin, R. The origins of iron. In *The Civilisation of Iron*; Nicodemi, W. Ed.; Olivares: Milan, Italy, **2004**; 135.

[5] Godfrey, E.; Van Nie, M.A. Germanic ultrahigh carbon steel punch of the late Roman-Iron age. *Journal of Archaeological Science* **2004**, *31*, 1117–1125.

[6] Giumlia-Mair, A. Roman metallurgy: workshops alloys, techniques and open questions. In *Ancient Metallurgy between Oriental Alps and Pannonian Plain. Workshop – Trieste, 29–30 October 1998*; Giumlia-Mair, A. Ed.; Associazione Nazionale per Aquileia, Casa Bertoli, Dipartimento di Ingegneria dei Materiali e Chimica Applicata, Università di Trieste, **2000**; 106–120.

[7] Giumlia-Mair, A.; Maddin, R. Iron and steel in the Roman period and in Late Antiquity. In *The Civilisation of Iron*; Nicodemi, W. Ed.; Olivares: Milan, Italy, **2004**; 113–142.

[8] Capotorto, C.; De Monte, G.; Gauzzi, F.; Verdini, B.; Violi, G. Metallurgical study of the ironworks of the 'round temple' of forum Boarium, Rome. *Metallurgical Science and Technology* **1995**, *13* (2), 57–64.

[9] Starley, D. Metallurgical study of an iron beam from Catterick Bypass. In *Caractonium, Roman Catterick and Its Hinterland. Excavation and Research 1978–1997*; Wilson, P.R. Ed.; Council for British Archaeology Report: London, UK, **2003**; 129, 166–171.

[10] Campbell, J.; Fahey, F. A metallurgical study of iron pile shoes from the Roman bridge at Minturnae. *Journal of the Historical Metallurgy Society* **1984**, *18* (1), 21–29.

[11] Wanhill, R.J.H.; Seimen, P.A.; Rijenberg, R.A.; Meijers, H.J.M. Investigating a broken pile-shoe from a Roman Bridge. *Historical Metallurgy* **2007**, *41* (1), 32–39.

[12] Angus, N.S.; Brown, G.T.; Cleere, H.F. The iron nails from the Roman legionary fort at Inchtuthil, Perthshire. *Journal of the Iron and Steel Institute* **1962**, *200*, 956–968.

[13] Pleiner, R. *Iron in Archaeology. Early European Blacksmiths*; Archeologický ústav AV ČR: Prague, Czech Republic, **2006**; 100.

[14] Dieudonné-Glad, N. L'acier dans les limes de l'Antiquité au Moyen Âge. Persistance des techniques. In Dillmann, P., Pérez, L., Verna, C. Eds.; *L'acier en Europe avant Bessemer*, Actes du Colloque International, Paris 8–10 décembre 2005, *Série Histoire et Techniques*, CNRS/Université-Le Mirail, Méridiennes, **2011**; 175–193. ISBN : 978-2-912025-70-8

[15] Cato *on Agriculture*, 2, Humphrey, J.W., Oleson, J.P., Sherwood, A. N. trans.; *Greek and Roman Technology: a sourcebook*. **2006**, Routledge, London, 91.

[16] Maddin, R.; Hauptmann, A.; Weisberger, G. Metallographische Untersuchungen an römischem Gezähe aus Rio Tinto, Spanien. *Metalla* **1996**, *3* (1), 27–44.

[17] Epprecht, W.; Schaller, E. Eisen und Stahl aus Vindonissa, *Gesellschaft pro Vindonissa* **1981**, 29–52.

[18] Sim, D.; Ridge, I. Examination of a moulding plane blade from Vindolanda. *Historical Metallurgy* **2000**, *34* (2), 77–82.

[19] Pearson, C.E.; Smythe, J.A. Examination of a Roman chisel from Chesterholm. *Proceedings University of Durham Philosophical Society*, **1931–1937**, *9*, 141–145.

[20] Peacock, D.P.S.; Maxfield, V.A. *Survey and Excavation Mons Claudianus 1987–1993*, Institut français d'archéologie orientale: Paris, France, **1997**; 1, 192, 200, 251–253.

[21] Hirt, A.M. *Imperial Mines and Quarries in the Roman World. Aspects 27 BC –AD 35.* Oxford, UP, **2010**; 63.

[22] Schneider, H. *Einführung in die antike Technikgeschichte*, Wissenschaftliche Buchgesellschaft: Darmstadt, **1992**; 72.

[23] Cleere, H. The Roman Industry of the Weald and its connections with the *Classis Britannica*, *Archaeological Journal* **1974**, *131*, 171–199.

[24] Young, T. Roman military control on iron-making in South Wales. In *Early Iron in Europe*; Cech, B., Rehren, Th. Eds.; Monographies Instrumentum 50, Éditions Monique Mergoil: Montagnac, **2014**; 215–225.

[25] Bishop, M.C.; Coulston, J.C.N. *Roman Military Equipment*, 2nd Ed.; Oxbow Books: Oxford, UK, **2006**; 232–244.

[26] Fulford, M.; Sim, D.; Doig, A. The production of Roman ferrous armour: A metallographic survey of material from Britain, Denmark and Germany and its implications, *Journal of Roman Archaeology* **2004**, *17*, 197–220.

[27] Caesar. The Gallic War, Book 1, 26, Vol. 39. Edwards, H.J. Trans., The Loeb Classical Library Harvard University Press: Cambridge, MA.

[28] Renoux, G.; Dabosi, F.; Pailler, J.-M. Les armes en fer d'Uxellodunum (Puy d'Issolud, Lot), dernière bataille de César en Gaule: Etude paléométallurgique de pointe de fleche et trait de catapulte. *Revue d'Archéométrie* **2004**, *28*, 141–152.

[29] Lang, J. Study of the metallography of some Roman swords, *Britannia* **1988**, *19*, 199–216.

[30] Biborski, M.; Kaczanowski, P.; Kędzierski, Z.; Stępiński, J.; Ergebnisse der metallographischen Untersuchungen von römischen Schwertern aus dem Vindonissa-Museum Brugg und dem Römermuseum Augst. *Jahrbuch der Gesellschaft pro Vindonissa* **1985**, *1986*, 45–80.

[31] Williams, A.R. Roman arms and armour: a technical note, *Journal of Archaeological Science*, **1977**, *4*, 77–87.

[32] Tylecote, R.F.; Gilmour, B.J.J. *The Metallography of Early Edge Tools and Edged Weapons*, BAR British Series 155; BAR: Oxford, UK, **1986**; 164–165.

[33] Lang, J.; Jackson, R. Scientific examination of the ring-pommel sword said to be from Pevensey, East Sussex. *The British Museum Technical Research Bulletin* **2015**, *9*, 87–96.

[34] Glimour, B.J.J. Victims of crime? Ferrous technology and origins of two pattern-welded swords from Durovernum Cantiacorum (Canterbury, Kent). In *Proceedings of the 1st International Conference, Archaeometallurgy in Europe*, Milan, Italy, Sept 24–26, 2003 Associazione Italiana di Metallurgia: 250–261.

[35] Lang, J. A metallographic examination of eight Roman daggers from Britain. In *Sites and Sights of the Iron Age*, Raftery, B., Megaw, V., Rigby, V. Eds.; Oxbow Monograph 56: Oxford, **1995**; 119–132.

[36] Corretti, A., Chiarantini, L., Benvenuti, M., Cambi, F. The Aithale Project: Men, Earth and Sea in the Tuscan Archipelago (Italy) in Antiquity, Perspectives, aims and first results. In *Early Iron in Europe*, Cech, B. and Rehren Th. Eds.; Monographies Instrumentum 50, Édition Monique Mergoil: Montagnac, **2014**; 181–195.

[37] Diodorus of Sicily, History, 5.13, 1–2. In *Greek and Roman Technology: A Sourcebook*; Humphrey, J.W., Oleson, J.P., Sherwood, A.N. Trans., Routledge: London/New York, **1998**; 219.

[38] Benvenuti, M.; Pecchioni, E.; Chiarantini, L.; Mariani, L.; Mascaro I. An investigation on iron smelting furnaces from the Etruscan site of Baratti – Populonia (Tuscany), In *Proceedings of the 6th European Meeting on Ancient Ceramics (EMAC'01) Fribourg, 3–6 October 2001*; Di Pierro, S.; Serneels, V.; Magetti, M. Eds., Department of Geosciences, Mineralogy and Petrography University of Fribourg, **2003**; 1–17.

[39] Voss, O. The Iron Production in Populonia, in PACT 21. In *The First Iron in the Mediterranean*; Sperl, G. Ed.; PACT: Belgium, **1988**; 91–100.

[40] Crew, P. The Iron and Copper slags at Baratti, Populonia, Italy. *Journal of the Historical Metallurgy Society* **1991**, *25* (2), 109–115.

[41] Crew, P.; In decline or prohibition? The end of prehistoric iron working in North Wales. In Benoit, P., Fluzin, P. Eds.; *Iron Paleometallurgy and Cultures Proceedings of the Symposium of UISPP Comité de la Sidérerugie Ancienne*, Belfort, Édition Vulcain: Paris, **1990**, 217–228.

[42] Cleere, H.; Some operating parameters for Roman iron works. *Bulletin of the Institute of Archaeology* **1976**, 233–246.

[43] Cleere, H.F.; Crossley, D. *The Iron Industry of the Weald*. Leicester University Press: Leicester, **1985**; 35.

[44] Pleiner, R. *Iron in Archaeology. The European Bloomery Smelters.* Archeologický ústav AV ČR: Prague, **2000**; 88–89.

[45] Morin, D.; Rosenthal, P.; Fontugne, M. Roman-early medieval iron mining and smelting at high altitude in the Alps

(Argentera-Mercantour massif - Alpes-Maritimes, France). *Antiquity* **2007**, *81*, 313. http://www.antiquity.ac.uk/projgall/morin1/

[46] Pleiner, R. *Iron in Archaeology. The European Bloomery Smelters.* Archeologický ústav AV ČR: Prague, **2000**; 131–195.

[47] Paynter, S. Innovations in bloomery smelting in Iron Age and Romano-British England. In *Metal and Mines: Studies in Metallurgy*; La Niece, S., Hook, D., Craddock, P. Eds.; Archeotype Publications in association with the British Museum: London, **2007**; 208.

[48] Salter, C. The scientific investigation of the iron industry in Iron Age Britain. In *Analysis in Archaeology*; Henderson, J. Ed.; Oxbow Press: Oxford; 250–273.

[49] Domergue, C.; Cauuet, B.; La Vieille, E.; Pailler, J.-M.; Sabayolles, R.; Sillières, P. *Un centre sidérurgique roman de la Montagne Noire, le domain des Forges (Less Martys, Aude)*; Paris CNRS 1993, 477p (Supplement à la RAN; 27).

[50] Gassmann, G. Recent discoveries and excavations of 6th-2nd century BC furnaces in SW Germany. *Historical Metallurgy* **2002**, *36* (2), 71–76.

[51] Dunikowski, C.; Cabboi, S. *La sidérugie chez les Sénons: les ateliers celtiques et gallo-romaines des Clérimois (Yonne),* DAF, 51, Paris 1995.

[52] Crew, P. Laxton revisited: a first report on the 1998 excavations, *Journal of the Historical Metallurgy Society* **1998**, *32* (2), 49–53.

[53] Salter, C.; Ehrenreich, R. Iron metallurgy in central southern Britain, In *Aspects of the Iron Age in Central Southern Britain*; Cunliffe, B., Miles, D. Eds.; Committee for Archaeology Monograph no. 2., University of Oxford: Oxford, **1984**; 146–161.

[54] Paynter, S. Regional variations in bloomery smelting slag of the iron age and Romano-British periods, *Archaeometry* **2006**, *48* (2), 271–292.

[55] Paynter, S. Innovations in bloomery smelting in Iron Age and Romano-British England. In *Metals and Mines*; La Niece, S., Hook, D., Craddock, P. Eds.; British Museum Press: London, **2007**; 209.

[56] Crew, P.; Charlton, M. The anatomy of a furnace and some of its ramifications. In *Metals and Mines*; La Niece, S., Hook, D., Craddock, P. Eds.; British Museum Press: London, **2007**; 219–225.

[57] Dillmann, P.; L'Héritier, M. Slag inclusion analysis for studying ferrous alloys in French medieval buildings: supply of materials and diffusion of smelting processes. *Journal of Archaeological Science* **2007**, *24*, 1810–1823.

[58] Blakelock, E.; Martinón-Torres, M.; Veldhuijzen, H.A.; Young, T. Slag inclusions in iron objects and the quest for provenance: an experiment and a case study, *Journal of Archaeological Science* **2009**, *36*, 1745–1757.

[59] Pagès, G.; Dillmann, P.; Fluzin, P.; Long, L. A study of the Roman iron bars of Saintes-Maries-de-la-Mer (Bouches du Rhône, France). A proposal for a comprehensive metallurgical approach. *Journal of Archaeological Science* **2011**, *38*, 1234–1252.

[60] Crew, P. The experimental production of prehistoric bar iron, *Historical Metallurgy* **1991**, *25* (1), 21–36.

[61] Tylecote, R.; Austen, J.N.; Wraith, A.E. The mechanism of the bloomery process in shaft furnaces, *Journal of the Iron and Steel institute* **1971**, *209*, 342–363.

[62] Dungworth, D. Metalworking debris from Elms Farm, Heybridge, Essex. Centre for Archaeology, Report 69/2001, London, English Heritage.

[63] Wright, J.H. Metallurgical examination of a Roman iron beam from Catterick Bridge, Yorkshire, *Historical Metallurgy Group Bulletin* **1972**, *6*, 24–28.

[64] Fluzin, P.; Bauvais, S.; Berranger, M.; Pagès, G.; Dillmann, P. The multidisciplinary approach (archaeology and archaeometry) to bloomsmithing activities in France: examples of results from the last twenty years. In *The Archaeometallurgy of Iron*; Hošek, J., Cleere, H., Mihok, L. Eds.; Institute of Archaeology of the ASCR: Prague, **2011**; 223–236.

[65] Fluzin, P. Premiers résultats des etudes métallographiques concernant les masses de métal brutes. In *Alle origini della siderurgia lecchese*; Tizzoni, M., Cucini, C., Ruffa, M. Eds.; Richerche archaeometallurgiche ai Piani d'Erna: Lecco, **2006**; 129–146.

[66] Smythe, J.A. Ancient Sussex iron blooms: a metallographic examination. *Transactions of the Newcomen Society* **1936/1937**, *17*, 197–203.

[67] Brown, G.T. Roman bloom from Cranbrook. Kent, *Journal of the Iron and Steel Institute* **1954**, *202* (1), 502–504.

[68] Dubois, C. Lercoul (Pyrénées ariégeoises). Un site sidérurgique du III^{e} s. de notre ère. Mines et métallurgies en Gaule. Recherches récentes, *Gallia* **2000**, *57*, 1–158.

[69] Cech, B. The production of *ferrum Noricum* at Hüttenberg, Austria - the results of archaeological excavations carried out from 2003 to 2010 at the site Semlach/Eisner. In *Early Iron in Europe*; Cech, B., Rehren Th. Eds.; Monographies Instrumentum 50, Édition Monique Mergoil: Montagnac, **2014**; 17.

[70] Cucini, C.; Tizzoni, M. Iron production in Lombardy from the 2nd century BC to the 6th century AD. In *Early Iron in Europe*; Cech, B. and Rehren Th. Eds.; Monographies Instrumentum 50, Édition Monique Mergoil: Montagnac, **2014**; 173–180.

[71] Coustures, M.-P.; Dieudonné-Glad N.; Dillmann, P.; Béziat, D. Tentative chemical characterisation of a Roman smelting workshop (Oulches, France). In *Early Iron in Europe*; Cech, B. and Rehren Th. Eds.; Monographies instrumentum 50, Édition Monique Mergoil: Montagnac, **2014**; 93–116.

[72] Berranger, M.; Fluzin, P. Organisation de la chaîne opératoire en métallurgie du fer aux IIe-Ier siècle av. J.-C. sur l'oppidum d'Entremont (Aix-en-Provence, Bouches-du-Rhône): la circulation de mêtal, *Revue d'Archéométrie*, **2007**, *31*, 7–22.

[73] Berranger, M. Le Fer entre matière première et moyen d'éxchange, en France du VII an Ier s. BCE. Approaches pluridisciplinaires. PhD thesis. University of Paris 1, **2009**.

[74] Crew, P.; Crew, S. Currency bars in Great Britain, typology and function. In *La sidérurgie ancienne de l'Est de la France dans son context européen. Archéologie et archéométrie.* Annales litéraires de l'Université de Besançon (Paris: Les Belles Lettres) **1994**; 345–350.

[75] Straube, H. *Ferrum Noricum* und die Stadt auf dem Magdalensberg, Springer: Wien/NewYork, **1996**; 126–134

[76] Schaaber, O. IV Metallkundliche Untersuchungen an Fundstücken aus Schweiβstahl vom Magdalensberg; *Archiv für das Eisenhüttenwesen* **1964**, *35* (6), 502–506.

[77] Naumann, F.K. Untersuchung alter Fundstücke von den Ausgrabungen am Magdalensberg in Kärnten. *Archiv für das Eisenhüttenwesen* **1964**, *35* (6), 495–502.

[78] Pleiner, R. Iron in Archaeology. The European Bloomery Smelters, Archeologický ústav AV ČR: Prague, **2000**; 272.

[79] Buchwald, V.F. *Iron and steel in ancient times.* Historisk-filosofiske Skrifter 29, Det Kongelige Danske Videnskabernes Selskab, **2005**; 110–111.

[80] Zwicker, U. Ein Werkzeugstahl des Saturnius, *Bayerische Vorgeschichtsblätter*, **1996**, *61*, 245–246.

[81] Personal communication: Dr J. Stępiński

[82] Pagès, G.; Dillmann, P.; Fluzin, P.; Long, L. A study of the Roman iron bars of Saintes-Maries-de-la-Mer (Bouches du Rhône, France). A proposal for a comprehensive metallurgical approach. *Journal of Archaeological Science* **2011**, *38*, 1241

[83] Durman, A. Iron resources and production for the Roman frontier in Pannonia, *Historical Metallurgy*, **2000**, *36* (1) 24–32.

[84] Bauvais, S.; Fluzin, P. Organisation of forging activities in Northern Paris Basin agglomerations (France) during the final La Tène. In *Early Iron in Europe*; Cech, B., Rehren Th. Eds.; Monographies instrumentum 50, Édition Monique Mergoil: Montagnac, **2014**; 133–146.

[85] Fluzin, P. Ponte di Val Gabbia III (Bienno). Les premiers résultats des études métallographiques. In *Il ferro nelle Alpi: giacimenti, miniere e metallurgia dall'antichità al XVI secolo: atti del convegno 2–4 ottobre1998 Bienno*; Cucini Tizzoni, C., Tizzoni, M. Eds.; Comune di Bienno, **2000**; 24–31.

[86] Mack, I.; McDonnell, G.; Muphy, S.; Andrews, P.; Wardley, K. Liquid steel in Anglo-Saxon England, *Historical Metallurgy* **2000**, *34* (2), 87–96.

[87] Crew, P.; Charlton, M.; Dillmann, P.; Fluzin, P.; Salter, C.; Trauffaut, E. Cast iron from a bloomer furnace. In *The*

Archaeometallurgy of Iron; Hošek, J., Cleere, H., Mihok, L. Eds.; Institute of Archaeology of the ASCR: Prague, **2011**; 239–262.

[88] Dieudonné-Glad, N.; Les Oulches. A late Roman smelting site, 2nd International Conference, Plas tan y Bwlch 17–21 September 2007: Early Iron working in Europe II. Archaeology, Technology, Experiment.

[89] Salter, C. Early steel in Britain; introduction, production and use. Abstract: 2nd International Conference, Plas tan y Bwlch 17–21 September 2007: Early Iron working in Europe II. Archaeology, technology, experiment.

[90] Bauvais, S. Evolution de l'organisation des activités de post-réduction dans le nord du basin-parisien au second âge du Fer: études multidisciplinaires de la chaîne opératoire en métallurgie du fer. Unpublished PhD thesis, University of Technology of Belfort-Montbéliard 2007.

[91] Cech, B. Die Produktion von Ferrum Noricum am Hüttenberger Erzberg. *Austria Antiqua* **2008**, *2*.

[92] Leroy, S.; Desaulty, A.-M.; Dillmann, P.; Terygeol, F.; Verna, C.; Bertrand, L. First examination of ore, slag and artefacts from the iron making site of Castel-Minier (Aulus-Les-Bains, 09) France, In *Proceedings of the 2nd International Conference*, Archaeometallurgy in Europe 17–21 June 2007 Aquileia CD-ROM.

[93] Lang, J.; Craddock, P.T.; Simpson, St.J. New evidence for early crucible steel. *Journal of the Historical Metallurgy Society*, **1998**, *32* (1), 7–14.

[94] http://www.leesauder.com/pdfs/Aristotle's%20Steel.pdf

[95] Pleiner, R. *Iron in Archaeology. The European Bloomery Smelters*; Archeologický ústav AV ČR: Prague, **2000**; **133**.

[96] Dillman, P.; Terygeol, F.; Verna, C. Premières analyses metallographiques des produits sidérurgiques, trouvés sur le site medieval de Castel Minier (Aulus-les-bains 09), *Archéosciences* **2006**, *30*, 7–14.

[97] Truffaut, E. Steelmaking in a bloomer furnace: behaviour of manganese. In *Early Iron in Europe*; Cech, B., Rehren Th. Eds.; Monographies instrumentum 50, Édition Monique Mergoil: Montagnac, **2014**; 285–298.

[98] Sauder, L.; Williams, S. A practical treatise on the smelting and smithing of bloomery iron, *Historical Metallurgy* **2002**, *36* (2), 122–131.

[99] Pleiner, R. *Iron in Archaeology. The European Bloomery smelters*, Archeologický ústav AV ČR: Prague, **2000**; 190–193.

[100] Salter, C.J. Bloomery Steel – an overlooked material. In *Early Ironworking in Europe, archaeology and experiment*; Crew, P., Crew, S. Eds.; *Plas Tan y Bwlch*, **1997**; 83–84.

[101] Cleere, H. The Iron Industry of Roman Britain, 1981, Wealden Iron Research Group @ www.wealdeniron.org.uk, 64.