Chemical and isotopic characterization and production technique of subferrate asses of the Lyons Altar series (part 1)

Chemical and isotopic characterization and production technique of subferrate *asses* of the Lyons Altar series

Sabine Klein,
Hans-Markus
von Kaenel

The early Roman Imperial *AES* Coinage IV.

Content

Part I

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1. The find spot and the coin ensemble

A few years ago we conducted a study on the chemical composition and isotope ratios of copper coins of Augustus from the mint of Lyons/Lugdunum[1]. As a supplement we present in the following four *asses* from Gross-Rohrheim (Bergstrasse district, Hesse state, Germany), which are typologically attributable to this group and which do not consist of solid copper but of an iron core surrounded by a copper skin *(Fig. 1–5)*. Due to the conditions of the soil, the iron core of three of the four coins is strongly corroded, has formed bubbles in the copper shell and has blown them up in individual places *(Fig. 1.3–5)*. The four coins were discovered within the framework of systematic field surveys agreed with the Landesamt für Denkmalpflege Hessen – hessenArchäologie, Aussenstelle Darmstadt, and are part of a remarkable new ensemble of Roman finds from the right bank of the Rhine, which will be presented elsewhere[2] and discussed in the context of the early Roman finds from southern Hesse[3].

The four subferrate Lyons Altar *asses* are part of an important early imperial ensemble comprising around 160 coins, which consists of Roman Republic *asses*, coins of the Augustan moneyers series and from Nîmes/Nemausus as well as *asses* and *semisses* of the Lyons Altar series[4]. The series of 19 silver coins ends with six denarii for Caius and Lucius Caesares as *principes iuventutis*[5] minted around the birth of Christ. Silver from the reign of Tiberius is missing. The most recent coins are two Tiberian *asses* of the DIVVS AVGVSTVS PATER series[6], one of the type RIC I² 72 (circa 15/16 AD) and another of the type RIC I² 81 (probably early, middle, and late Tiberian). The represented countermarks fit well into the type repertoire of the late Augustan/early Tiberian countermarks on the Upper Rhine[7].

Thanks to the finder's, J. Lotter, courtesy, one of the four *asses* (No. 4) could be divided into two parts *(Fig. 4.5)* for the purpose of a detailed technological and analytical investigation. We are therefore in a position to precisely document and describe the coin in question, to reconstruct its manufacture and to characterise the metals geochemically. In addition, the isotope ratios for the copper used are determined and discussed.

2. Subferrate Lyons Altar *asses*

The adjective subferrate *(nummus subferratus)* represents a modern word creation[8] formed according to the Latin term *(nummus) subaeratus*[9]. If the core cannot or should not be differentiated, one generally speaks of "plated coins". Subaerate coins in the form of republican and imperial *denarii* and *quinarii* as well as Gallic silver coins are common. An overview of more than 3500 Late Latène, Republican and Augustan/Tiberian silver coins from 20 significant sites in northern Gaul and the Rhine areas, compiled by the author, shows that about 75 % of them consist of solid silver, while about 25 % are clad silver coins. For 377 silver coins from the reigns of Augustus and Tiberius the ratio is 65 % : 35 %. Among the individual finds from the Roman colony of *Augusta Raurica,* 104 (32 %)[10] of the 326 silver coins are subaerate. The mass of the cores consists of

1 Klein et al. 2012; the other contributions: Klein et al. 2004; Klein – von Kaenel 2000.
2 M. Helfert – H.-M. von Kaenel – J. Lotter (in preparation); for a republican denarius from the find spot with graffiti see Kemmers – Scholz 2017.
3 Maurer 2011.
4 The quantitative ratio between the coins of the Altar series I : II is about 1 : 2.
5 Werz 2018a; Woytek – Blet-Lemarquand 2017; Wolters 2002; for the distribution of the type Wolters 2017, pp. 48–55; Berger 1996, pp. 25–31.70–73 (lists).
6 For the dates of the two types see Barrandon et al. 2010 and Klein – von Kaenel 2000, pp. 75–79.
7 On the current state of discussion, which is controversial in many respects, see Martin 2018; Werz 2018b; Wigg-Wolf 2018; Wolters 2018.
8 *Sub* (beneath) *ferrum* (iron).
9 *Sub* (beneath) *aes* (copper, bronze); documented in Persius, Satires V, 106.
10 Peter 2004, p. 21, note 9.

copper, iron cores are comparatively rare. The production of plated coins was not limited to the Roman and Gallic minting, rather there are already corresponding Greek coins[11].

The question of how plated silver coins are to be legally judged has long been the subject of controversy; a consensus has emerged, though not universal, in favour of interpreting such coins as counterfeit money[12]. However, the one-sided discussion from the point of view of Roman law has greatly narrowed the view of the complexity of this remarkable phenomenon. Plated coins were widespread and a reality also outside the sphere of Roman law. Which practices were developed locally in dealing with plated coins – and which negotiation processes took place to define value and equivalence in connection with the acceptance and distribution of these coins – are at least as interesting aspects as the legal assessment "genuine" or "false"[13]. Against this background, the considerations of M. Pfisterer[14], differentiated in terms of content and terminology, on the interpretation of subferrate *aes* and cast coins are helpful.

After a series of pioneering works[15] on the *nummi subferrati,* important contributions to the subferrate coinages from the late 2nd and first decades of the 3rd century AD in Noricum and Pannonia[16] recently appeared. In this context, the production technique of subferrate coins[17] also received due attention. In 2017, an international team of authors led by J.-M. Doyen, St. Martin and M. Peter presented the first systematic and comprehensive study[18] on subferrate *aes* coinages of the Roman Imperial Period. On the basis of a compilation of nearly 1800 corresponding coins from the four Gallic, the two Germanic provinces as well as *Raetia,* the *Alpes Poeninae, Noricum* and *Pannonia,* the study provides a systematic geographical, chronological and typological overview of the different groups of subferrate copper and brass coins. At the current state of knowledge[19], however, subferrate coins appear to be very rare in Italy, the Spanish provinces and Britain.

The practice of minting Lyons Altar coins by surrounding an iron core with a thin copper skin is part of a larger context. As the systematic study clearly shows, in the Julio-Claudian period in Gaul and on the Rhine subferrate *aes* coins imitating coin types of Augustus, Tiberius, Claudius and Nero occur, whereby those after Augustan types obviously make up the majority[20]. These also show the widest distribution in Gaul and on the Rhine, whereas subferrate *aes* coins based on types of Tiberius, Claudius and Nero seem to concentrate rather on the Lower Rhine. But even after that period, subferrate coins were still produced in this area until the end of the 2nd century. In the course of the second half of the 2nd century the production of subferrate and cast coins began in the middle Danube basin[21]. Parallel to the subferrate *aes* coins of types of the Julio-Claudian emperors, masses of imitations[22] in copper, more rarely in brass, which were of poor manufacture and style and heavily underweighted, circulated in Gaul and on the Rhine.

The subferrate specimens representing the Lyons Altar series I and II[23] are usually *asses,* rarely *semisses* (series II). In the repertory of the comprehensive study, a total of 90 corresponding coins[24] are listed for the territory of the present Netherlands (5), Belgium (4), France (36), Luxembourg (23), Germany (11) and Switzerland (11). They account for about 75 % of the 120 subferrate coins

11 Olsen et al. 2020; van Alfen 2005; Moesta – Franke 1995, pp. 35–36.106–109.

12 Crawford 1968; RRC pp. 560–565; Crawford 1985, pp. 187–191; Peter 2011; Peter 2004; problematic, however Debernardi 2010.

13 Important for the relevant written sources and their discussion Pfisterer 2007b, pp. 765–768.

14 Pfisterer 2007a, p. 642; Pfisterer 2007b, pp. 768–772.

15 Dembski 1993; Zedelius 1988; Zwicker – Dembski 1988; van Heesch 1987; Thirion 1975.

16 Pintz 2014; Pfisterer 2007a; Pfisterer 2007b; Pfisterer 2006.

17 Haubner et al. 2016; Pfisterer 2007b; Pfisterer – Traum 2005a; Pfisterer – Traum 2005b; Zwicker – Dembski 1988.

18 Doyen et al. 2017.

19 Doyen et al. 2017, pp. 207–208 with map 1.

20 Doyen et al. 2017, p. 217 Fig. 8.

21 Doyen et al. 2017, pp. 229–232 with maps 6–13.

22 Martin 2015, pp. 294–312; Nüsse 2014; Doyen 2007, pp. 120–124; Wigg-Wolf 2004; Wigg-Wolf 1996, pp. 424–436; Giard 1970.

23 Altar series I, ca. 7–3 BC (RIC I² 230; van Heesch 1993); Altar series II, ca. 8 (?)/9–14 AD (RIC I² 233. 237. 238. 242. 245). – On the numismatic and historical classification of the two coin types Klein et al. 2012, pp. 65–72; Doyen 2007, pp. 51–62; Giard 1983.

24 Doyen et al. 2017, pp. 227 (map 2).280–294 (lists).

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by coin types from the reign of Augustus. In addition to subferrate Lyons Altar coins, subferrate specimens from Nîmes/Nemausus and – rarely – moneyers *asses*[25] also occur. The authors of the study rightly assume that a considerable number of unreported subferrate coins is to be expected because they were not recognizable as such in view of their generally poor state of preservation[26]. On account of the magnetism of the iron core, a magnet however would easily indicate the special manufacture of these coins[27]. Unfortunately, the lists of the systematic study as a whole do not contain any information on the style and manufacture of the subferrate coins; if one consults original publications[28] with illustrations, then it becomes apparent that the subferrate Lyons Altar coins are not exclusively, but often imitations *(Fig. 3)*.

As a comparison with the distribution map of the *asses* of the Lyons Altar series I[29] in Gaul and on the Rhine compiled by F. Berger shows, the occurrence of subferrate specimens of the series I is precisely classified in this category. The coins in question are found not only in military camps, but also in civil settlements and sanctuaries. In quantitative terms, however, they seem to have played a marginal role. The Augustan period ensemble from the sanctuary of La Villeneuve-au-Châtelot (Aube) consists of 1282 Celtic and Roman coins, including 558 *asses* from the Lyons Altar series I with a total of seven (1.2 %) subferrate specimens[30]. Five (1.0 %) of the 477 corresponding coins from the Colony of Augusta Raurica[31] are subferrate. The fantastic quantities of subferrate coins postulated by a co-author of the comprehensiv study are therefore to be regarded as implausible: *"Dès lors, c'est sans doute par dizaines de millions, voire par centaines de millions qu'il faut estimer la production globale des subferrati"*[32].

As far as the date of production of subferrate *aes* coins is concerned, the study distinguishes between two chronologically and territorially clearly separated phases, a first in the early imperial period (20/30–60/70 AD) and a second in the second half of the 2nd and the first of the 3rd century AD (around 160–260 AD)[33]. In the first phase, which mainly affects Gaul and the Rhineland, subferrate *asses* (copper/iron) dominate, in the second (Noricum, Pannonia) subferrate brass coins (brass/iron)[34].

For the subferrate Lyons Altar coins, the above-mentioned chronological approach, the justification for which is not very convincing, remains to be specified. One of the arguments for the beginning of the production of such coins during the reign of Augustus is the following: The ensemble of La Villeneuve-au-Châtelot, found in 1973 was, as it turned out after its discovery, part of a Gallo-Roman sanctuary, which was subsequently excavated. The coin series consists of 32 silver wheels, 66 Gaulish and 1184 Roman coins; the most recent coins[35] are 558 *asses* of the Lyons Altar series I and 225 coins from Nîmes/Nemausus of the type RPC I 524. The countermarks represented on the coins in the ensemble of La Villeneuve-au-Châtelot are part of a late Augustan horizon with, among others, ten VARVS countermarks[36]. Since there are no countermarks that can be clearly identified as Tiberian, there is much to suggest that the ensemble represents a part of ritual deposits from the late Augustan period. Among the 558 asses of the Lyons Altar series I a total of seven subferrate *asses*[37] are documented. The coin series from Gross-Rohrheim now also provides a

25 Peter 2001, p. 53 vs. Doyen et al. 2017, p. 215.
26 Doyen et al. 2017, pp. 208–209.211.
27 Zwicker et al. 1993, p. 233.
28 *Augst*: all 5 subferrate Lyons *asses* are imitations: Peter 1996, pp. 161–162 Inv.-No.1958.11927 (series II). p. 233 Inv-No. 1959.9348 (series I). Inv.-No. 1960.5429 (series I). p. 345, Inv.-No. 1968.5979 (series II). p. 353 Inv.-No. 1969.6292 (series II). – *Martberg:* 8 subferrate Lyons *asses,* from which 7 are imitations: FMRD IV 4,1, 4001, 1, No. 1205 (series I, regular). No. 1272 (series II, imit.). No. 1291 (series II, imit.). No. 1328–1331 (series I/II, imit.); FRMD IV, 4001, 6, No. 599 (series I/II, imit.). – *Xanten:* 1 subferrate *as,* imitation: Komnick 2015, p. 64 No. 631 (barb?).
29 Berger 1996, Fig. 20.21.
30 Zehnacker et al. 1984, pp. 61.77–84.
31 See note 28; Doyen et al. 2017, p. 283–284; Peter 2001, pp. 53–54.
32 Doyen et al. 2017, p. 226.
33 Doyen et al. 2017, pp. 215–216.219–220.
34 Doyen et al. 2017, pp. 243–280 (lists); Pfisterer 2007b.
35 Zehnacker et al. 1984, pp. 41–44 No. 402–626 (Nîmes/Nemausus). pp. 45–54 No. 627–1184 (Lyons Altar series I).
36 Zehnacker et al. 1984, pp. 77–84. – The governorship of Varus on the Rhine began in 7 AD and ended in the disaster of 9 AD.
37 See note 30.

chronologically important indication. They also suggest the production of subferrate Lyons Altar coins already in reign of Augustus in central/northern Gaul, including the Rhine basin. It is an area with a strong local tradition of minting coins in the Late Latène period. With the beginning of the difficult process of Romanization of the *Tres Galliae*[38] under Augustus, in which Roman structures were also enforced against resistance, the local minting activity did not disappear but changed. This is not only supported by "romanized" coin emissions such as RPC I 506[39], 508[40] and 509, but also "Gallic" ones such as the AVAVCIA bronzes[41], as well as imitations and subferrate coins that differ from their manufacture, weight, style and design.

The reason for the local minting activity lay in the scarcity of small change caused by the gradual monetarization of the *Tres Galliae*[42], to which the stationing of large contingents of troops on the Rhine much contributed. Although considerable quantities of regular copper coins were available, the official mints in the Julio-Claudian period – unlike for the precious metal – did not cover by far the demand for small coin units. This *laisser faire – laisser aller* policy left room for local minting activities for decades. Whoever stood behind the relevant workshops, individual personalities, communities, troops, "counterfeiters", these coinages evaded a simple, generally binding categorization into "genuine" or "false" in practice. The Roman provincial authorities did not intervene because they did not suffer any damage as a result, but the financial administration determined the form in which taxes and duties were accepted (gold, silver coins, certain goods)[43]; coins in copper were not one of them. Moreover, the individual taxpayer did not pay his taxes directly to the *fiscus,* but to the local authority to which he belonged, and it was this entity which paid the total amount of the tax fixed for it.

We know nothing about how the mass of imitations and also subferrate copper coins – as far as they were recognized as such – were dealt with in everyday life during the early imperial period in Gaul and on the Rhine. Since there is no evidence that attempts had been made to enforce "bad" small change at the official nominal value, it must have been left to local negotiation processes between the actors concerned to determine the value at which corresponding coins changed hands locally. The material value, metal and weight, will have represented the decisive criteria.

Altogether, the production of subferrate Lyons Altar coins documents a very revealing but quantitatively unimportant aspect in the complex and protracted process of monetarization of vast territories in the northwestern provinces of the Roman Empire.

38 Arbabe 2017, pp. 103–169; Dondin-Payre 1999.

39 Type Scheers 1983, 216; Doyen 2007, pp. 63–85.

40 See the remarkable number of about 1500 coins of this type from the source of Bourbonne-les-Bains (Haute-Marne) in Sauer 2005, pp. 18.248–276; Doyen 2007, pp. 90–93.

41 Type Scheers 1983, 217; Aarts et al. 2009; in this context important the deposit of about 100 coins of the type Scheers 1983, 217, see pp. 822–823. pl. XXVI no. 746, with lead cores and very thin copper skins *(nummi subplumbati)*; see Burkhardt 1989, p. 30; Ilisch 1999, pp. 285–286 and below note 96.

42 Delestrée 2017; Martin 2015, pp. 177–250; Martin 2011; van Heesch 2009; van Heesch 2005; Giard 1970.

43 For the collection of taxes De Ligt 2009; for the financial matters see Martin 2015, pp. 208–212.

3. Description and documentation of the examined coins from Gross-Rohrheim from a metallurgical point of view

3.1. The coins

Series I (7–3 BC?)[44]

Obv.: CAESAR PONT MAX. Laureate head of Augustus to the right.
Rev.: ROM ET AVG. Altar of Roma and Augustus at Lugdunum.
RIC I^2 230

No. 1 *(Fig. 1)*
Found in 2009 by J. Lotter; Find No. 090138. – 11.52 g; Diameter 2.66 cm.
Obv.: Above strong corroded marginal part, below burst bubble. Rev.: Strong corrosion in the marginal parts and in the centre.

Fig. 1: coin 1 (scale 1:1)

Series II (8 ?/9–14 AD)

Obv.: TI CAESAR AVGVST F IMPERAT V or VII. Laureate head of Tiberius to the right
Rev.: ROM ET AVG. Altar of Roma and Augustus at Lugdunum.
RIC I^2 238a. 245.

No. 2 *(Fig. 2)*
Found in 2008 by J. Lotter; Find No. 081213. – 10.31 g; Diameter 2.42 cm; Die axis: 240°.
Imitation; clumsy letters on the obv.
Obv.: Well preserved dark patina; under the bust and above the head of Tiberius the iron core becomes visible.

Fig. 2: coin 2 (scale 1:1)

44 For the chronology of the two series see note 23.

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Only available as photo:
No. 3 *(Fig 3)*
Found by M. Paulsen.
Obv.: Identification secured by letter remains and the ribbons of the wreath; strong encrustation and traces of corrosion at the edges, burst bubble in front of the face of Tiberius. Rev.: Right part of the altar recognizable; strong encrustation and corrosion.

Fig. 3: coin 3 (scale 1:1)

Series I/ II

No. 4 *(Fig. 4)*
Found in 2008 by J. Lotter; Find No. 081 215. – 10.86 g; Diameter 2.68 cm.
Obv. and rev. decentered. Obv.: Head to the right, strong corrosion and burst blisters. Rev.: Strong corrosion and large bubble, partly cracked.
Cut into two parts for this research with the permission of the finder J. Lotter *(Fig. 5)*.

Fig. 4: coin 4 (scale 1:1)

Fig. 5: coin 4 (scale 2:1). Left: cut in two halfs; right: cut surfaces

To the best of our knowledge, no specimen of the early imperial group of subferrate *aes* coins of interest here has yet been analyzed and discussed with regard to its production process. On the other hand, important studies are available on the *aes* imitations with iron cores from the late 2nd and early 3rd centuries AD, but their occurrence is concentrated on the middle Danube in Austria[45]. A number of contributions[46] have dealt with the metallurgy and production techniques of these coins.

The primary analytical investigation was carried out on composite coins[47] with the focus on Faustina II subferrate coins imitating corresponding *sestertii* and found at Enns and *Flavia Solva* in Austria. They discovered that the Enns coins were made of iron coated with a thin layer of Cu-Sn alloy (bronze), whereas the coins from *Flavia Solva* were coated with Cu-Zn (brass). From their modern appearance, the subferrate composition of the coins is obvious, as the original surfaces of the coins are inflated by iron corrosion. Earlier analytical and metallographic studies also showed a certain diversity in the production technique, which will be summarized later in this text.

The more complex composition and structure of the substrate coins requires detailed analytical and metallographic investigation, and valuable information cannot be obtained by non-destructive surface methods such as portable X-ray fluorescence spectrometry, minimally invasive portable laser ablation samples or surface leaching techniques, as these methods cannot penetrate into the rust-free core. This study examines and compares the subferrate coins of interest with an experimentally produced blank by R. Traum and M. Pfisterer, Vienna, using minimally invasive methods. In addition to the element and isotope analysis of the components, the focus here is on the microstructural identification of the composition of the iron core and copper layer as well as on technical aspects. The metallographic observation is limited to one (coin 4 – *Fig. 4*) of the four subferrate coins, which we were allowed to halve and thus study microstructural details. A polished profile was prepared for metallography. Coins 1 and 4 *(Fig. 1, Fig. 4)* were sampled by micro-drilling for the element and isotope composition, coin 3 was only available as a photo *(Fig. 3)*.

Since the subferrate Lyons Altar as analyzed here was found in a completely different area and manufactured almost 200 years earlier than the *aes* coinages with iron core in the Danube basin, we first discuss our results from the point of view of the distribution area of the Lyons Altar series in Gaul and on the Rhine. Due to the lack of metal analytical investigations of subferrate *aes* coins from the early imperial period, we will also discuss the contributions dealing with the subferrate silver coins[48] of this time.

3.2. The iron flan

The iron flan has concave rounded (barrel-shaped) edges and is clearly consistent in the thickness of 2.1–2.05 mm. The slightly wavy surface *(Fig. 6)* on the peripheral surface of the iron flan is visible and is certainly caused by the impact of the iron flan prior to the coating process. Barrel-shaped edges occur when a steel rod is used and cut into slices. By flat hammering the slices, blanks of equal diameter can be produced[49].

45 See note 16.
46 See note 17.
47 Zwicker– Dembski 1988.
48 Anheuser 1998; Anheuser – Northover 1994; Zwicker et al. 1993.
49 Pfisterer – Traum 2005a, p. 139 pl. 8; further description of their technique see Pfisterer – Traum 2005b.

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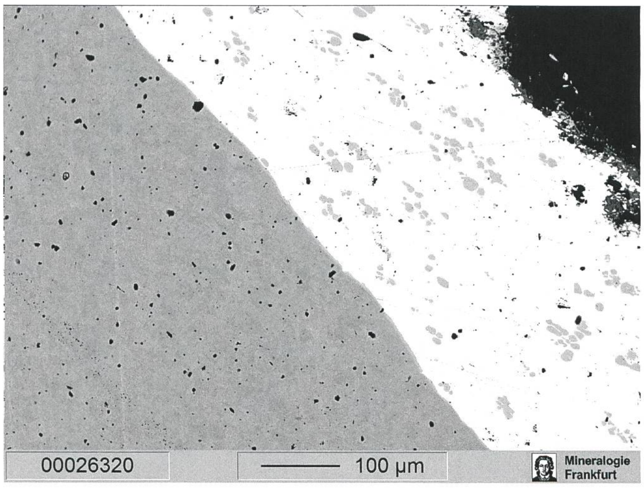

Figure 6: Coin 4. Backscattered image (BSE), electron microprobe analysis: Wavy surface of the iron flan (left, BSE: grey) indicating the flattening process. Right in the image is the copper layer (BSE: white; coin is diagonally oriented). Upper right corner (black) is resin.

The metallographic examination of the halved subferrate coin 4 *(Fig. 5)* was performed on a polished section without and with etching using a polarized light microscope (Zeiss Axiophot). Already as polished it becomes visible that the iron flan of the subferrate coin was made of homogeneous ferrous metal. Deformation twins in the iron flan[50] (Neumann lines) are not present here. Etching with a 2 % nital solution, an oxidizing etchant of nitric acid in ethanol, is usually used for the formation of Fe-C microstructures and shows a ferrite-pearlite microstructure *(Fig. 7),* which consists of hypoeutectic iron and thus the carbon content is < 0.8 % C. Overheated areas are located at the edges of the flan *(Fig. 9).* Based on the microstructure of the coin, the carbon content of the iron flan is even more accurate at 0.4 % C. This composition is consistent with other studies investigating subferrate coins with different archaeological contexts, appearance and composition of the coating (copper, tin, zinc and lead – a *"buntes Gemisch"*[51]): Low-carbon steel[52] (< 1 % C[53], 0.15 % C[54]) is reported. The low carbon content and the slag inclusions *(Fig. 8)* indicate the use of bloomery iron for the production of the iron flan. The low carbon content of the iron is typical for the entire Roman Empire[55]. An analysis is performed for an iron core in context of subaerate coinage consisting of wrought iron (99.8 % Fe, 0.07 % Ni, 0.06 % Sn) with a ferritic equiaxed grain structure[56].

50 Haubner et al. 2016.
51 Colourful mix, see Pintz 2014, p. 218.
52 Haubner et al. 2016.
53 Pintz 2014.
54 Zwicker – Dembski 1988.
55 Pintz 2014.
56 Anheuser – Northover 1994, p. 24 coin no. 5

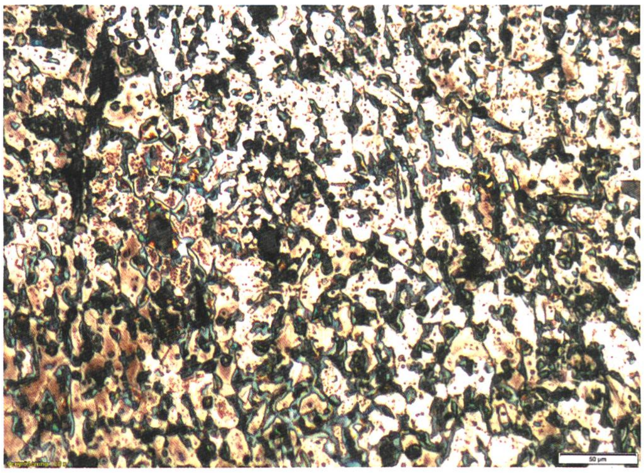

Figure 7: Iron flan of coin 4 as etched with Nital. Hypo-eutectic structure comprises of ferrite (bright) and perlite (dark), which is a characteristic of iron with < 0.8 % C. (magnification = 20 ×).

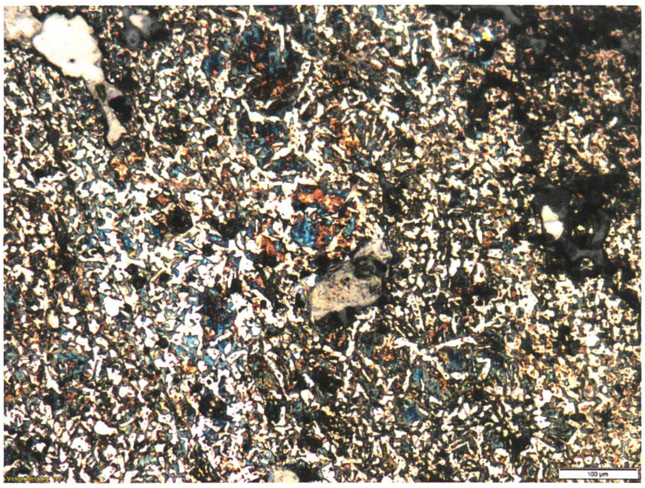

Figure 8: Iron flan of coin 4 as etched with Nital. View towards the edge of the coin, where needle-like ferrite-perlite structure developed, which forms when hypo-eutectic Fe-C with < 0.8 % C was overheated (magnification = 20 ×).

3.3. The copper layer

The copper layer of coin 4 is homogeneously 0.4–0.3 mm thick *(Fig. 9).* Copper has no microstructural relation to the iron flan. The interface is sharp and there is no material exchange. The adhesion of the copper metal to the iron is without solvent and also without bonding layer and therefore of high quality. The close bond protects the iron from oxidation and corrosion. In the copper layer, dendritic or spherical iron is homogeneously distributed as a metal throughout it *(Fig. 10).* The presence of iron in the metallic state is strongly supported by observation with SEM, where the iron inclusions appear with exactly the same brightness as the metallic iron flan. Iron oxide or silicate phase would appear darker than the iron flank in a backscattered image. Theoretically iron has a limited solubility in copper. Iron can reach 2.8 % in at 1010 °C (s) melting temperature in the copper, and can rise continuously up to 20 % at 1400 °C[57].

57 Craddock – Meeks 1987; Smelting temperatures of pure copper: 1085,5 °C, of pure iron: 1535°C. Taking-up rate of iron in copper see phase diagram Fe-Cu (http://www.ams.org.cn/article/2014/0895-3988-1224/grp1E39.jpg.html)

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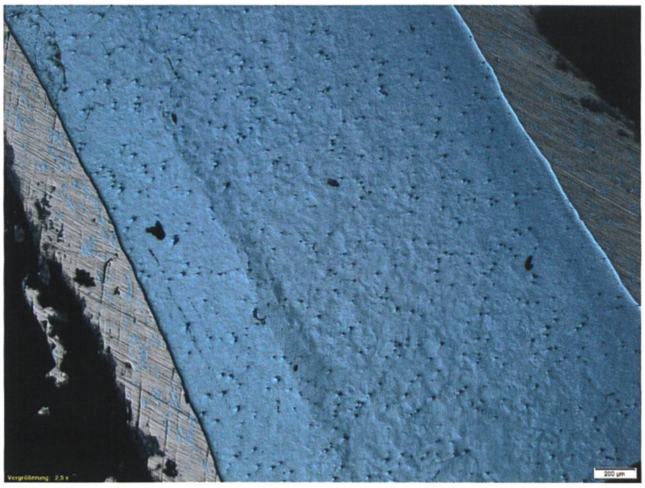

Figure 9: Polarized microscope, cross polished section of the subferrate coin 4 as polished. Core (blue) = iron flan, layer (brown/blue) = copper layer. The thickness of the copper layer is 300–350 μm.

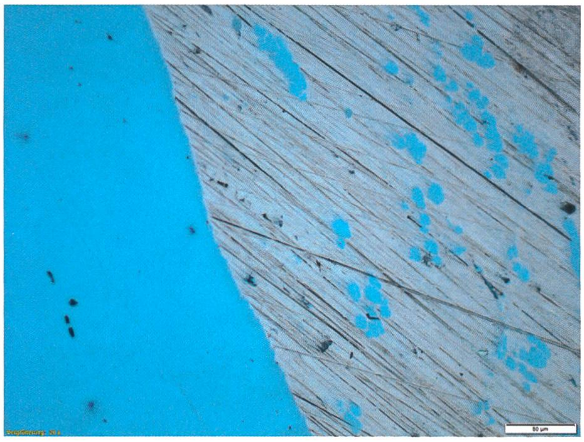

Figure 10: Polished section of subferrate coin 4. The coin is diagonally oriented in the image. Interface between iron flan and copper layer. Left: Iron flan (in blue), right is the copper layer (beige), in which dendritic α-iron (blue) is distributed homogeneously throughout the copper layer, but iron and copper is not in interfacial exchange between the two materials. The interface between iron and copper is sharp with the iron flan being passively protected from corrosion by the covering copper layer. The joint is very tight without any oxidation occurring. No solder has been used either.

Sectional images are presented in the literature[58] as etched demonstrating that their iron flan was a low carbon steel with 0.15 % which was heated to about 1000 °C. It was suggested that at this temperature molten iron could dissolve in the copper metal. Deformation twins (Neumann lines) in the microstructure of an iron core are suggested to indicate that the embossing was performed after cooling of the flan[59]. The technique of dipping the iron flan in molten (copper) metal was confirmed for their example. Backscattered images of "drop-shaped iron precipitates in copper plating"[60] occur very close to the interface between coating and core. They are caused by the interaction between the molten copper (alloy) and the iron flan when iron droplets from the flan enter the copper (alloy) layer. This would require that the iron flan at least melts superficially to move as droplets into the molten copper (alloy), but only indicates operating temperatures around the melting point of the copper alloy which would not exceed

58 Zwicker – Dembski 1988, p. 16 Fig. 2.3.
59 Haubner et al. 2016.
60 Haubner et al. 2016, p. 450.

S. Klein, H.-M. von Kaenel: Chemical and isotopic characterization and production technique of subferrate *asses* of the Lyons Altar series, SM 70, 2020, S. 3–21.

1030 °C and thus would not reach the required temperature level to move the iron in the molten state. Alternatively, solid-state reaction diffusion[61] is described as a process in which iron moves from the solid flan into the coating melt (alloy) forming a so-called diffusion zone. The latter phenomenon is explicitly explained as a solid iron-melt-copper reaction, and many images can be found in the literature to visualize the interfacial diffusion effects. It is underlined by a description of iron that is *"interfaced to copper at the bottom by way of dendritic... iron"*[62].

In contrast to these descriptions, the appearance of the iron inclusions in the copper layer of coin 4 differs from such observations and earlier published images[63], as the iron does not spread from the iron flan into the copper layer and is not an enriched zone at the interface of the two. The presence of spheroid and dendritic α-iron therefore cannot be interpreted as exchanged and detached from the underlying iron or as diffused into the (molten) copper during the coating process. Another explanation made in literature that stirring with an iron rod in molten copper would introduce iron into copper metal[64] is not a reasonable explanation here, because it seems inappropriate to us that the melting temperature of iron was reached for the coating process that would have been required for melting iron from the stirring rod into the copper.

Another explanation for the presence of metallic iron in the copper layer concerns surface chips as residues from the forging process of the iron flan (iron scale), which contaminate the iron flan surface and are thus introduced into the (molten) copper layer if the iron surface has not been thoroughly cleaned prior to the coating process[65]. This does not apply here either, because scale residues would appear sharp-edged by the mechanical process, but never dendritic or spherical.

Only at the edges of coin 4 do fractions occur in the copper layer which are sharp and ragged. Here, in contrast to the ob- and revers planes, the corrosion only penetrates deep into the iron flan. The iron flan is significantly dented here *(Fig. 11)*, which indicates that intensive stress particularly affected this area of the flan.

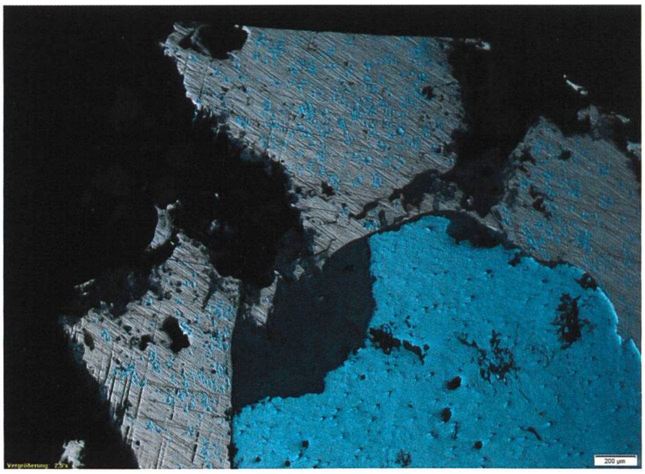

Figure 11: Coin 4. One of the two barrel-shaped edges of coin 4. The iron flan is significantly dented and the barrel shape is distorted. Where the copper sheet has broken apart, the iron flan is weakened and in consequence heavily corroded. The copper layer appears as cut surfaces.

61 Zwicker – Dembski 1988, p. 15.
62 IshidaA 1986, Fig. 8; s. also Craddock – Meeks 1987, p. 199.
63 Pintz 2014, p. 219; Haubner et al. 2016, pp. 448–449; Zwicker – Dembski 1988, p. 16. Varieties in copper plating composition is reported, gun-metal, a Cu-Pb-Sn-Zn leaded red brass.
64 Cooke – Aschenbrenner 1975, p. 253.
65 pers. comm. R. Traum, March 14, 2017.

Etching the copper layer of the subferrate coin reveals the laminar structure with compressed and elongated grains parallel to the iron flan planes. No annealing twins or slip lines can be observed, so that cold forming is indicated as the process used. Around the edges of the subferrate coin, the microstructure is dominated by more equiaxed grains *(Fig. 12)*. Remembered is the etched microstructure of the iron flan at the edges, which indicates overheating. The overheated microstructure is discussed in context to subaerate/subferrate coins as a consequence of applying a wrapping sheet with subsequent and slight heating to bond the metals[66].

This reinforces the fact that the ob- and reverse planes of the coin had passed through different temperature conditions and stress than the edges from the coating and joining process, which had affected the edges more than the ob- and reverse planes. Also, the laminar structure resulting from cold working of the copper layer along the planes can be considered as an effect of the striking procedure.

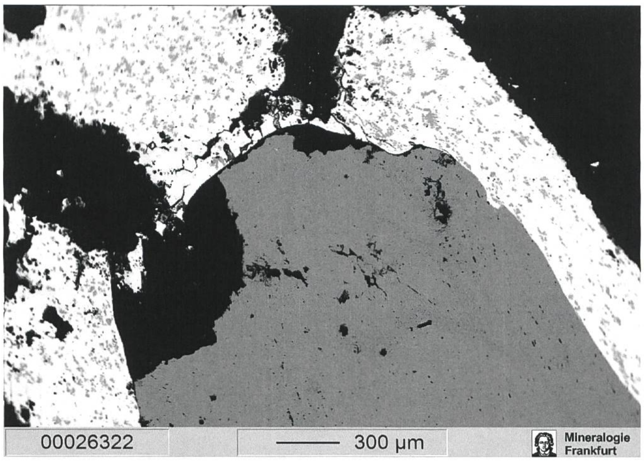

Figure 12: Backscattered image (EPMA). Microstructure of the copper layer on the plane sides of the coin (laminar structure) is different from the edges (equiaxed structure).

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66 Scott – Schwab 2019; Anheuser – Northover 1994, p. 30: "*... to plate their cores, the Romans wrapped them in pure silver foil and heated them rapidly to close to the melting point of silver for a short time, no more than a few minutes.*"

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Sabine Klein (Metallurgie, Analytik, Technik)
Forschungsbereich Archäometallurgie
Deutsches Bergbau-Museum Bochum
Am Bergbaumuseum 31
44791 Bochum, Germany
sabine.klein@bergbaumuseum.de

and also

Frankfurt Isotope and Element Research Center (FIERCE)
Goethe-Universität Frankfurt am Main
60438 Frankfurt am Main, Germany

Hans-Markus von Kaenel (Archäologie, Numismatik)
Goethe-Universität Frankfurt am Main
Institut für Archäologische Wissenschaften, Abt. II
Norbert-Wollheim-Platz 1
60629 Frankfurt am Main, Germany
v.kaenel@em.uni-frankfurt.de

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