

Borrower: TXM
Lending String: *TUC,TJC,TKN,FQG,FTU

Patron: Clark, Victor
Charge: \$0.00

Journal Title: Archaeometry.

Call #: CC1 .A71
Location: 2nd Floor - Bound

Volume: 15 **Issue:**
Month/Year: 1973 **Pages:** 221-228

Article Author:
Article Title: L. H. Cope; The Metallurgical
Examination of a Debased Silver Coin of
Maximinus Daza Issued by Constantine I

Imprint: [Oxford] Oxford University, Research
Lab

ARIEL

Fax: (615) 898-5551
Ariel: 161.45.205.82

Mailed under Section 135.14 Postal Manual
LIBRARIES MATERIALS
POSTMASTER: This parcel may be opened for postal inspection if necessary.

FROM: Interlibrary Loan
University of Tennessee at Chattanooga
615 McCallie Ave / Lupton Library
Chattanooga, TN 37403

RETURN POSTAGE GUARANTEED

TO: TXM
Library/ILL
Middle Tennessee State University
Box 13
1500 Greenland Drive
Murfreesboro, TN 37132

University of Tennessee at Chattanooga Interlibrary Loan
ILLiad TN: 82804 ILL #: 30958526

THE METALLURGICAL EXAMINATION OF A DEBASED SILVER COIN OF MAXIMINUS DAZA ISSUED BY CONSTANTINE I

L. H. COPE

UKAEA Reactor Group, Risley, Warrington, England

EDITORIAL NOTE

Paper originally delivered, on behalf of the author, by Mr E. Calvert, at the Symposium on Archaeology and Archaeological Prospection, Oxford, 17 March 1972, under the title of 'The place of wet chemical metallurgical analysis in archaeological research'.

Although archaeologists are generally willing to contemplate the complete destruction of unique sites, by excavation, they often show an inconsistent reluctance to destroy even fairly common artifacts for the scientific information which they can provide. There is, therefore, a predilection towards non-destructive methods of chemical analysis—despite the many uncertainties which attend their use, and which often lead to the acquisition of unreliable and misleading information with respect to the compositions of the *original* materials from which coins or other artifacts were made.

It is unfortunate that non-destructive methods of chemical analysis almost always involve variable factors of uncertainty. This is partly due to indirect measurements having to be made by means of physical phenomena which may not be chemically specific and free from matrix or other interference effects, and partly because of the unknown extents of internal heterogeneity and corrosion upon either the complete object or the fractional sample taken. (The effects of segregation and corrosion are, however, unlikely to be properly discerned without recourse to some form of destructive examination.)

In consequence, the concept of a destructive metallurgical examination, and chemical analysis by absolute methods is often abandoned prematurely with insufficient regard to their full potentialities of reliability, accuracy, and completeness.

The objective, here, is to advise that the classical techniques of metallurgical analysis can best meet the needs of archaeological research; and that they should be preferred wherever they can be justified in that the scientific information which they can provide will exceed the value of the object destroyed or damaged in the process. But let it be quite clearly understood that total destruction is not always involved. It is often possible to perform a satisfactory destructive analysis on quite a small sample, provided that the sample itself is known to be truly representative of the bulk. A one-gramme sample is often adequate for the accurate determination of the individual major alloys and impurities to as close as 0.01%, and will also provide a metallographic sample for the study of the internal structure which can reveal the entire mechanical and thermal history of the artifact. The chemical composition can then be much more fully understood in the light of the revealed phase-structure of the matrix and other subsidiary structures and compounds present. If necessary, the metallographic specimens can be used later to provide a most detailed electron-probe study of individual

phases; and this will show local variations in composition, and concentrations of segregated elements, which are blurred by the bulk analysis but are of great value to our understanding of the manner in which the object was made from its basic ingredients.

The main objective of a chemical analysis is to reveal qualitatively the elements present in the sample, and to determine the proportion of each one which is of any significance. Wet chemical methods of analysis do enable the individual elements to be positively identified and selectively and sequentially isolated and determined in a proper quantitative manner. Analysis procedures can also be chosen to avoid interferences by matrix effects, and to eliminate the uncertainties which are associated with most indirect physical methods used for element separations in non-destructive procedures. It is recognized that there are some alternative and valuable physical methods of analysis, but they should be really regarded as adjuncts to the standard chemical methods rather than as substitutes for them.

The principles of destructive analysis advocated are best illustrated by an example: and so this paper deals with the not unusual case of a coin for which all known means of non-destructive chemical analysis would have been quite unsuitable—and even misleading with respect to the true nature and composition of the original alloy used for its manufacture. On the other hand a deliberately planned destructive examination has revealed the true composition of the original alloy (and hence its calculable intrinsic worth); the processes of mint-fabrication; and both the earliest and the much more recent corrosion mechanisms. Although the as-received coin weighed only 2.42 g, a full chemical analysis, a check analysis for fineness, an analysis of the surfaces and a full metallographic examination, were all performed; and a quarter of the original coin still remains for any further work which may be required by posterity.

The immediate problem posed was that of the fineness of a Constantinian *nummus argenteus**—of apparently debased silver alloy—of c. A.D. 312–13. The known features of this coinage are described in considerable detail by Sutherland (1967). But although Diocletian's reform of the Roman Imperial Coinage, in A.D. 294, was a major landmark in its history, we still lack any scientific evidence of the fineness of the apparently high quality silver pieces which he introduced, or of any of the subsequent changes under the tetrarchic and later administrations. The main reason is that these pieces have been generally regarded as too rare to allow sacrifice for analysis—despite the potential numismatic value of a reliable assay.

The opportunity to examine a later issue in the same series was provided, however, by Mr R. A. G. Carson, in December 1971. A suitable coin, similar to that depicted in plate 1, had been generously donated by Mr K. J. J. Elks, and was put at complete disposal for analysis. As a collector's piece it was regarded as a very inferior specimen—although there was no doubt about its identity. It was a moderately worn and corroded example of RIC vi Trier 826, minted for Constantine, in the name of Maximinus Daza, c. A.D. mid 311–May 313. Its 17 mm die-circle was well centred on an evenly spread 18 mm flan. The coin surface was slightly corrosion-pitted, but there were no obvious adherent corrosion products—although some were later discovered entrapped in and beneath the superficial porous over-layers of enriched silver. The drab silver-grey external appearance justified Sutherland's

* This type of coin is sometimes called a *denarius argenteus*. Its original description was, until recently, unknown. But the term *argenteus* can now be attested as having been in contemporary use (cf. K. T. Erim, J. Reynolds and M. Crawford, JRS (1971), p. 175), so the description *nummus argenteus* is used here as being the most appropriate in the light of existing knowledge.

description of the pieces of this series as 'base silver' (Sutherland 1967) and the baseness was both confirmed and determined, by the subsequent chemical analyses.

From earlier studies of surface-silvered coins (Cope 1972a), it was suspected that the coin comprised a low-grade silver alloy interior which had been surface-enriched with silver either during coin fabrication or by subsequent corrosion. (This proved to be so, since both elevated-temperature and aqueous corrosion influences were shown to have been involved during manufacture, and in archaeological time, respectively.) A metallographic examination was, therefore, deemed to be the first necessity—to discover the structures of both the interior and the surfaces, and the nature of the transition between them; and to detect if there was, indeed, sufficient uncorroded core material to provide an analysis safely judged to be properly representative of the original coinage alloy and the melt from which it came.

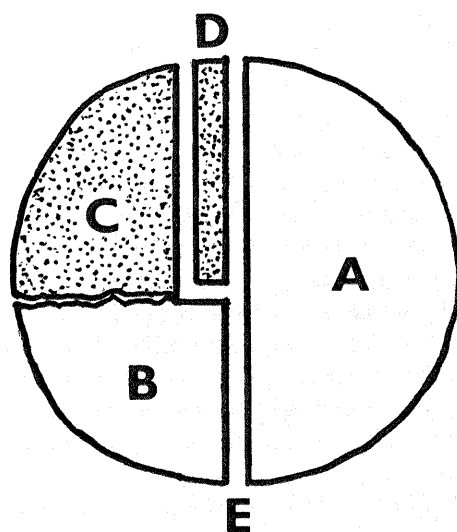


Figure 1 The division of the coin into sections for metallographic examination and chemical analysis. A. Main analysis sample: filed free from silvering and superficial corrosion, then deoxidized by fusion in a hydrogen atmosphere. B. Subsidiary analysis sample: filed clean, then dissolved for the separation of gold, antimony, and arsenic. C. Archive specimen: preserved (with surface intact) in the British Museum. D. Metallographic specimen: still preserved in its acrylic plastic mount. E. Saw cuttings: used for a neutron activation analysis check of the gold:silver ratio.

Accordingly, after visual examination and mensuration, the coin was sectioned in the manner illustrated in figure 1. The portions were then allocated to various analytical examinations, in order to provide the maximum amount of metallurgical and chemical information possible—with confirmation of the important major features by complementary procedures. Section C, with its as-received surface-silvering undamaged, is now deposited in the British Museum—in case it should be required for any future study.

A fine-toothed jeweller's saw was used for the sectioning, and also for the radial slit necessary to initiate the desired fracture between the sectors B and C. This wasted very little material from the most important and useful central coin section; but the saw cuttings (sample E) were used to good account for a neutron-activation check on the gold/silver ratio determined on the other samples by chemical means. The sawn faces revealed a central core

of yellowish alloy loosely coated with a thin friable silver-grey outer skin. (Some of the detached flakes of the drab surface-silvering were then found to contain 44% of silver.) The uncorroded core alloy was fairly tough, and the fractured surfaces of sectors B and C exhibited a fine-grained uniform structure of a pale salmon-pink colour, indicating: (1) the presence of a considerable proportion of copper in the alloy; (2) a fairly uniform alloy composition; and (3) the presence of very little lead—which tends to embrittle copper-silver alloys and to produce a pale grey tinge in the fracture if present in even small percentages.

The metallographic specimen D was cold-mounted in acrylic plastic for the examination of the polished cross-sectional face, and care was taken to preserve intact as much of the friable surface material as possible. The corroded surfaces were, however, carefully filed from sectors A and B, until there was no sign of remaining corrosion penetration. As a further precaution against leaving any invisible intercrystalline corrosion residues in the main analysis sample A, it was finally fused in a high-purity graphite capsule in a hydrogen atmosphere. It lost, thereby, a mere 0.75% of its weight, to yield a fully deoxidized alloy button of 0.8260 g for the principal bulk analysis sample.

Sector B, after mechanical cleaning, was separately dissolved in strong nitric acid, for the extraction of gold and tin, and for the separation of antimony and arsenic by co-precipitation with an iron hydroxide carrier. The opportunity was taken, during these chemical separations, to perform a check assay of the proportion of silver in the same sample.

The filed surfaces—unavoidably 'contaminated' with some of the sound interior coin alloy—were analysed first, as a guide to what to expect of the bulk alloy (on the assumption, proved later, that they might be derived entirely from it). The results are detailed in the first analysis column in table 1. The total of all the metallic elements separated was 95.61%: the remaining 4.39% was presumed to be mainly oxygen (and some chlorine) which were both detected in the entrapped corrosion products. The silver content of these mixed exterior constituents was found to be 33.74%—and hence they were much enriched in silver, compared with the base alloy.

In the subsequent exploratory analysis of the corrosion-free core sample taken from sector B, however, only 23.13% of silver was determined as the real content of the original coin alloy. On this sample Dr G. R. Gilmore (Universities Research Reactor, Risley, Warrington) also kindly performed a neutron-activation analysis of the dried mixture of the extracted original insolubles and the subsequent arsenic-antimony-iron co-precipitate. He confirmed the presence of tin, gold, arsenic, and antimony; and he then determined the proportions of those elements—which are shown in the last column of table 1 of analyses.

My own chemical analysis of the composition of the fused button sample—representing the original core alloy of the half-coin sector A—is given in the third analysis column of the table. The total of the conventionally determined elements amounted to 99.93%; and the addition of the separately determined antimony and arsenic contents brought this to a most satisfactory final analysis total of 100.04%.

The metallographic examinations proved to be extremely profitable. A low-power examination of the coin cross-section (plate 2) showed the bulk of the interior alloy—that portion which was taken for the main analysis sample—to be unaffected by either the main deep or more localized corrosion penetrations; although the superficially corroded layer was fairly thick, especially near to the more exposed coin rim.

The internal alloy structure (plate 3) was revealed, at higher magnification, to consist mainly of a copper-rich matrix which depicted evidence of minting by hot striking. There

Examination of a de

Table 1 Summary of

Emperor
Obverse
Reverse
Mint mark

Coin ref.
Dimensions
Die marks
Die axes
Weight
Appearance

Element

Copper
Tin
Silver
Lead
Iron
Nickel
Cobalt
Zinc
Gold
Arsenic
Antimony

Totals

Gold: silver ratio
(Au per 100)

Analysis

* This part
formed during
the initial
† Remains

were also seen
the dies in
of the two

Examination of a debased silver coin of Maximinus Daza issued by Constantine I 225

Table 1 Summary of chemical analyses. A debased silver coin of the Constantinian mint of Trier, minted A.D. mid-311–May 313

Table 1. Summary of data

minted A.D. mid-311–May 313

Code no. K.J.J.E.1

Emperor

Obverse legend

Reverse legend

Mint mark

Coin reference

Dimensions

Die module

Die axes

Weight, as received

Appearance

MAXIMINVS DAZA

IMP MAXI-MINVS AVG (radiate bust, left-facing)

SOLI INVIC-TO COMITI

|

PTR

RIC, vi, Trier 826

18–18.5 mm

17 mm (well-centred)

180°

2.42 g

Drab silver-grey

Chemical composition—weight per cent

Element	Exploratory analyses		Actual coin analysis	
	Filed surface layers from sectors A & B	Selected flakes of detached surface material	Solid core alloy from sector A (deoxidized)	Core alloy from sector B, filed clean
Copper	58.34	—	74.37	—
Tin	1.46*	—	1.06	[0.96±0.12]
Silver	33.74	44	22.75	[23.13]
Lead	1.64	—	1.24	—
Iron	0.08	—	0.35	—
Nickel	traces	—	traces	—
Cobalt	—	—	not detected	—
Zinc	0.13	—	0.03	—
Gold	0.22	—	0.13	[0.128]
Arsenic	—	—	—	0.041
Antimony	—	—	—	0.060
Totals	95.61%†		99.93%	100.04%
Gold:silver ratio (Au per 1000 Ag)	6.5		5.7	5.5
Analysts	Cope	Neutron activation assay by Gilmore	Cope	Neutron activation assays by Gilmore. Silver assay by Cope

* This probably includes some extraneous insoluble material—contaminating the β -meta-stannic acid formed during sample dissolution, and thus indicating a higher proportion of tin than the correct one for the internal alloy.

† Remainder, oxygen and some chlorine.

were also some traces of residual cold-work resulting from the superficial chilling effects of the dies in the final split-second of striking. The rather uneven microstructural distribution of the two principal phases is not unusual for wrought copper–silver alloys; but the obvious

heterogeneities provide full justification for using a gramme-size sample for chemical analysis, in order to give a high statistical probability of arriving at the true alloy composition of the original coin.

The unetched micrograph (plate 4) revealed a small proportion of lead (as particles of a slate-blue phase) seen against a ghostly background of the alpha- and beta-phases, the proportions of which indicated a silver content then roughly estimated to lie between 20 and 30%. The visible degree of macroscopic homogeneity revealed by the fractured surfaces of the coin was confirmed by the microstructural distribution of the principal phases, and was subsequently proved by the similarity of the finenesses of sectors A and B (which assayed 22.75% and 23.13% silver, respectively).

At the corroded surface of the coin a spongy network of the silver-rich alpha-phase was to be discerned—continuous with the identical phase in the body of the coin (plate 5). This was flattened and densified in places (plate 6) where the superficially oxidized copper matrix had been partly leached away, subcutaneously, by some pickling operation performed at the mint on the semi-finished coin blank.

In some zones (those not undermined by more recent corrosion in archaeological time) the outer layers of alpha-phase were packed closely together where the leaching of the oxidized matrix during the flan-preparation stages of coin fabrication had been most effective in removing the material which separated the skeletal silver-phase, and where the final hot-striking operation in minting had sufficed to consolidate it into a thickened but not fully forge-welded composite of silver-rich layers (plate 7).

The coin is clearly a so-called 'plated' coin, of the type which derives its silvered surface from the debased alloy in the course of fabrication stages involving intermediate hot-working and blanching* operations before final hot-striking. The drab appearance of the as-received coin is judged to be the consequence of more recent corrosion, which has both disturbed and contaminated the pristine appearance by the selective aqueous corrosion of the copper-rich phase of the core alloy matrix situated just beneath the porous surface layers of enriched silver.

The Diamond Pyramid Hardness of the interior alloy was also determined on the polished microstructural face of the core alloy section. A 10 kg load was used to enable a good average result, pertaining to the two phases present; and hardness values of 139 and 136 kg/mm² were measured in the two different positions. The hardness is observed to be about twice that which might be expected for an annealed or fully hot-worked Cu-Ag alloy of identical composition. The small amount of residual cold work seen in the microstructure would not have had a very significant effect; so it is concluded that the minted piece was very rapidly chilled after hot-striking (perhaps by quenching directly into a blanching liquid), and that it has subsequently age-hardened fully in archaeological time at soil and ambient temperatures.

We can now reflect on the alternative results which might have been obtained had there been no opportunity for a destructive metallurgical examination and analysis. In the first place, the fabrication history of the coin—as revealed so clearly by the metallographic studies—would have been completely undiscovered. Secondly, an X-ray fluorescence analysis—even if possible on the original rough surface of the coin—would have measured a

* A term sometimes used to describe the visible whitening which is consequent upon the dissolution of base metal oxides from the surfaces of oxidized silver alloys; this leaves a thin coating of unoxidized matte-white silver-rich material on the metal surface.

Plate 1 A typical spe
the British Museum.)



Plate 2 Cross-section
silvering and corrosion
x 16.

ample for chemical analysis of true alloy composition of

of lead (as particles of alpha- and beta-phases, the lead is reported to lie between 20 and 30% of the fractured surfaces of principal phases, and was found in A and B (which assayed

lead-rich alpha-phase was found in the coin (plate 5). This was due to the oxidized copper matrix and the corrosion performed at the

in archaeological time) the leaching of the oxide had been most effective use, and where the final surface had thickened but not fully

acquires its silvered surface during intermediate hot-drawing appearance of the surface corrosion, which has active aqueous corrosion beneath the porous surface

terminated on the polished surface used to enable a good surface values of 139 and 136 is observed to be about worked Cu-Ag alloy of silver in the microstructure of the minted piece was very fine (a blanching liquid), and fine at soil and ambient

been obtained had there been analysis. In the first by the metallographic (X-ray fluorescence analysis) would have measured a

upon the dissolution of base metal unoxidized matte-white silver.



Plate 1 A typical specimen of the coin analysed; RIC vi Trier 826. Actual size. (Photograph by courtesy of the British Museum.)

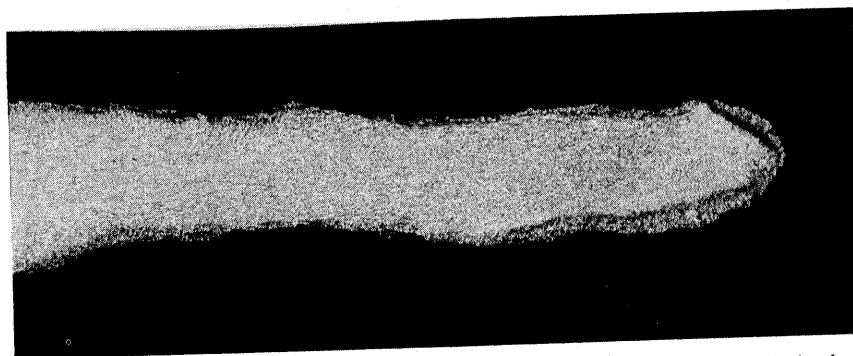


Plate 2 Cross-sectional macrograph, from the coin centre to its edge, showing variable depths of surface silvering and corrosion penetration but a substantial proportion of unaffected coin alloy interior. Magnification, $\times 16$.

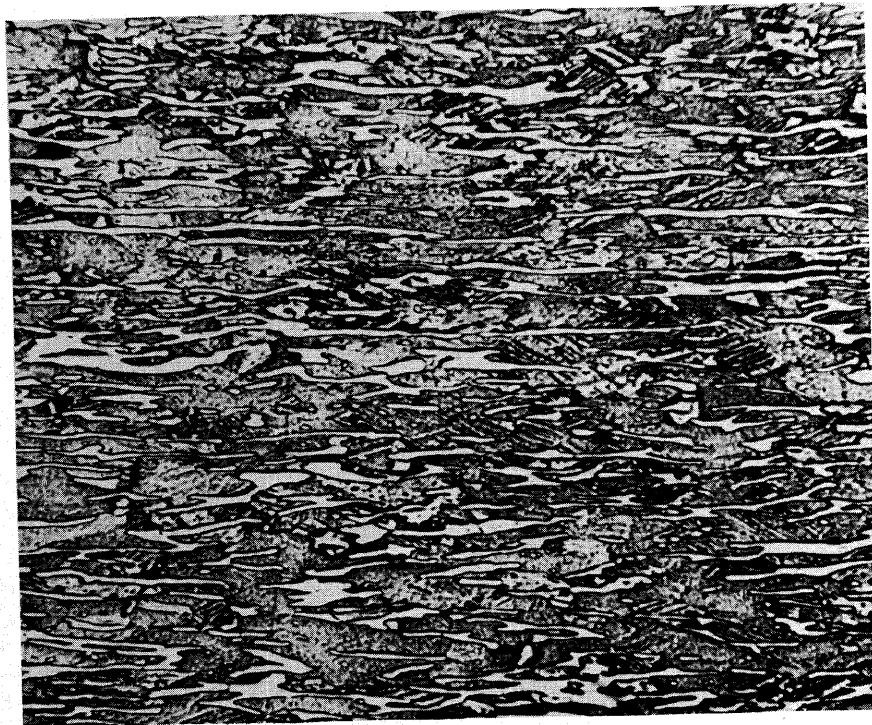


Plate 3 The internal microstructure of the coin alloy, depicting a distorted silver-rich (white) alpha-phase distributed within a copper-rich beta-phase matrix showing evidence of hot-working and traces of residual cold-work. Magnification $\times 500$.

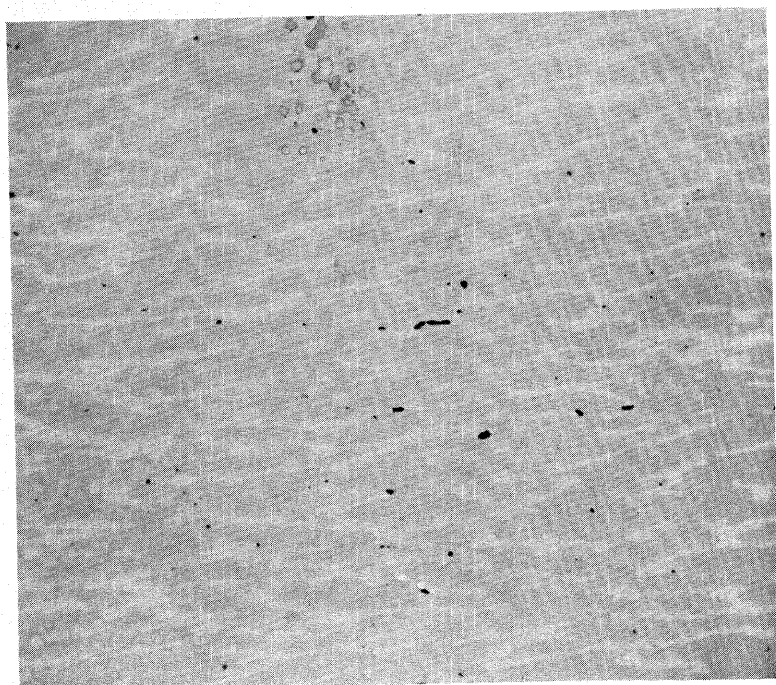


Plate 4 Dark particles of insoluble lead-phase seen against an unetched ghostly background of the deformed alpha- and beta-phases. Magnification $\times 500$.



(white) alpha-phase
+ traces of residual



end of the deformed

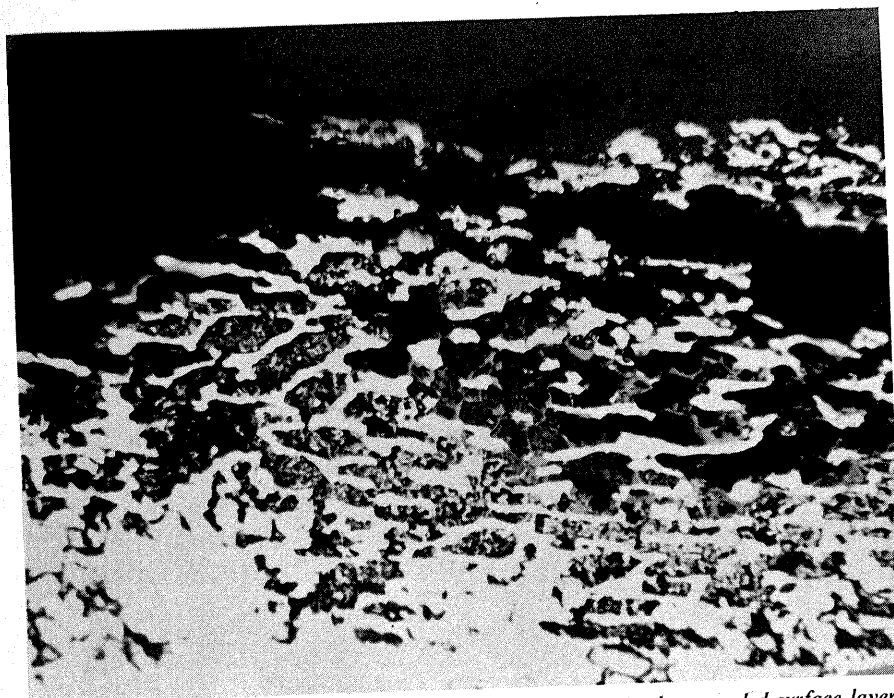


Plate 5 The spongy network of the original alpha-phase of the alloy in the corroded surface layers. In this region the beta-phase has been preferentially corroded to a depth of $15\mu\text{m}$ beneath the consolidated (but now missing) surface silver layer. Magnification $\times 500$.

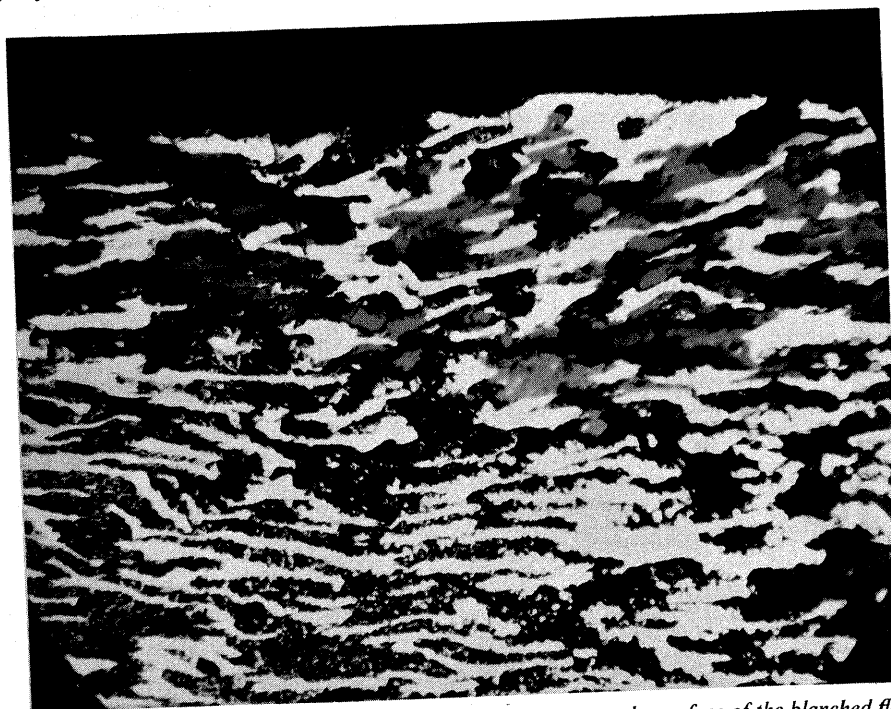


Plate 6 Here most of the original spongy alpha-phase network near to the surface of the blanching operation is seen to have been flattened and partly consolidated by the final coin-striking operation; but traces of oxidized and undissolved beta-phase still separate the silver-rich lamellae in places. Magnification $\times 650$.

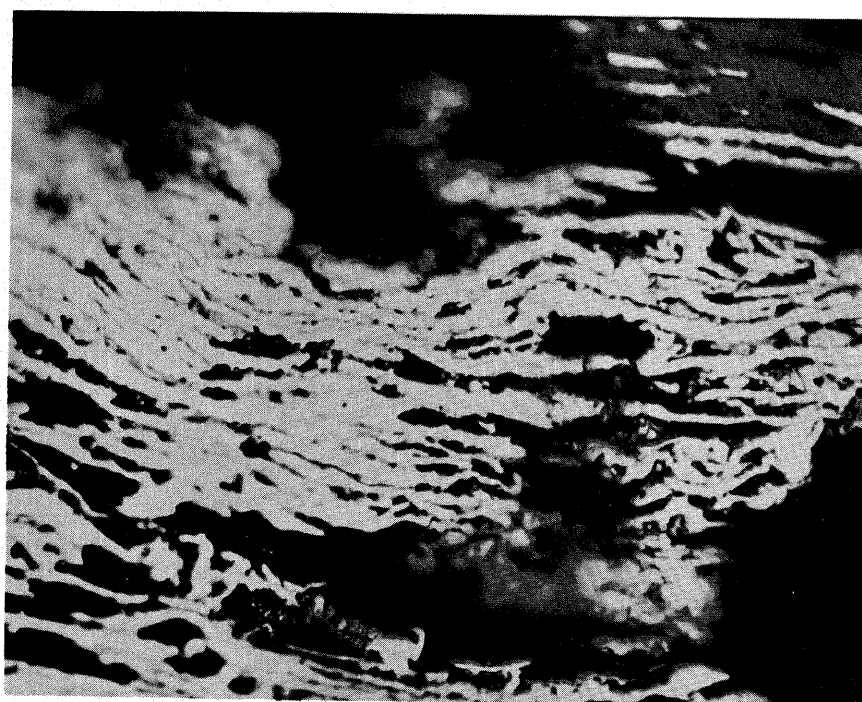


Plate 7 Photomicrograph of a cross-sectional area where the original 'plating' was intact. It can be seen to comprise fairly well-consolidated layers of silver-rich alpha-phase derived from the original microstructure of the coin-alloy flan. At this position it is about 50 μm thick. Magnification $\times 1000$.

Examination of a de-
 silver-rich surface decei
 spectrographic analysis
 of the mixed and corro
 and iron removal. Thir
 average 'smeared' resu
 alloy or the 'plated' I
 interpretations. Final
 with the corroded and
 alloy of even different
 indicating the real
 In contrast, howev
 welded full and othe
 minting technology;
 viously unknown 3
 argentiferous coinage
 position in the serie
 standing of its deno
 In RIC vi, the coi
 before the defeat of
 Carson (of the Briti
 belongs to the later
 of intrinsic worths (A.D. 312—for it sec
 1/72 libra Constans
 event, the earliest
 libra argentiferous
 short life suggests
 libra folles in a co
 not be suitably ra
 If, despite the lo
 able assumption
 tetrachic nummus
 would have posse
 in a 1/72 libra (Cope 1972b). C
 parallel series in
 the introduction
 equivalents of to
 to 8.5 to 1 and
 From these
 argenteus woul
 folles, for it to
 continue its mi
 change in its fi
 the nummus ar
 yet those alrea

silver-rich surface deceptively much finer than the true fineness of the solid core alloy. A spectrographic analysis would have been similarly limited to revealing only the composition of the mixed and corroded superflces, affected (as they were) by mild chloride contamination and iron removal. Thirdly, a neutron-activation of the whole coin could have yielded only an average 'smeared' result for fineness, which would have been incorrect for either the core alloy or the 'plated' layers as separate entities, and thus deceptive for any numismatic interpretations. Finally, a density determination would have been considerably influenced by both the corroded and the enriched layers, of dissimilar densities, originating from the coin alloy of even different density; and the result would have been quite useless for any attempt at indicating the real alloy composition.

In contrast, however, the combined destructive analysis and metallographic study has yielded full and otherwise inaccessible metallurgical information pertaining to the entire minting technology; and, for numismatic purposes, it has revealed the adoption of a previously unknown 3 uncia per libra fineness standard for an hitherto enigmatic issue of argentiferous coinage. It is now possible to locate the coin with much more confidence in its position in the series of contemporaneous commoner issues, and to reach a better understanding of its denominational relationship with them.

In RIC vi, the coin is considered to belong to the period after the death of Galerius, but before the defeat of Maximinus Daza, i.e. post-May 311, but pre-May 313. Mr R. A. G. Carson (of the British Museum) is, however, of the opinion that the particular coin analysed belongs to the later part of this period—say A.D. 312 to May 313. Indeed, a new consideration of intrinsic worths (detailed below) might further narrow the minting of this issue to the year A.D. 312—for it seems to be more probable that it was issued contemporaneously with the 1/72 libra Constantinian folles than with the 1/96 libra folles of early 313 to c. 318. In any event, the earliest issues of the type must have been issued in parallel with the extant 1/72 libra argentiferous bronze folles and to have been denominationally related to them. Their short life suggests that they become intrinsically incompatible with the weight reduced 1/96 libra folles in a coinage system in which the denominational value of the higher piece could not be suitably raised.

If, despite the lower weight of the worn and corroded piece examined, we make the reasonable assumption that the issue was minted to the 1/96 libra weight-standard of the earliest tetrachic *nummus argenteus*, an average mint-fresh coin (of the determined fineness standard) would have possessed a theoretical silver content of 0.846 g—compared with 0.0628 g of silver in a 1/72 libra Constantinian folles minted to the 4 scrupula per libra fineness standard (Cope 1972b). Consequently, the ratio of actual silver contents in typical coins of the two parallel series in vogue in A.D. 312 was 13.5 to 1; but this would have changed to 18 to 1 with the introduction of the 1/96 libra folles in early A.D. 313 (Cope 1970). In terms of the silver equivalents of total metal worths, however, the corresponding ratios might have been nearer to 8.5 to 1 and 11 to 1, for the 1/72 and 1/96 libra folles respectively.

From these calculated values it follows that the base-silver Constantinian *nummus argenteus* would have had to possess a denominational value of at least, say, ten 1/72 libra folles, for it to have been a practical proposition to retain it in parallel circulation and to continue its minting. But, with the reduction of the folles to 1/96 libra—without any apparent change in its fineness standard or denominational value (Cope 1972b)—the cost of minting the *nummus argenteus* would have risen out of all proportion to its existing valuation; and yet those already in issue could hardly have been raised to multiples of their former value. In

this event it would have ceased to be minted (perhaps before February A.D. 313) with the introduction of the 1/96 libra follis, at least three or four months before the elimination of Maximinus Daza. It is quite feasible that the continued need for a higher 'silver' denomination than the follis was then met by the immediate introduction of the VICTORIAE LAETAE PRINC. PERP. coinage—at a somewhat earlier date than that proposed by Bruun (1966) for the earliest issues of that series, and perhaps contemporaneously with the later issues of the smallest Sol folles (Cope 1972*b*).

REFERENCES

- Bruun, P. M., 1966, The Roman Imperial Coinage, VII. Spink & Son Ltd.
Cope, L. H., 1970, Die module measurements, and the sequence of Constantine's reformed folles issues of Spring A.D. 310 and of early A.D. 313. *Gazette Numismatique Suisse* 20, cahier 78, 46–60.
Cope, L. H., 1972*a*, Surface-silvered ancient coins, *RNS Special Publication* No. 8, 261–278.
Cope, L. H., 1972*b*, The metallurgical analysis of Roman Imperial silver and *Aes* coinage, *RNS Special Publication* No. 8, 3–47.
Sutherland, C. H. V., 1967, The Roman Imperial coinage, VI, 224. Spink & Son Ltd.