NOTAE NUMISMATICAE
ZAPISKI NUMIZMATYCZNE

Tom XX

MUZEUM NARODOWE W KRAKOWIE
SEKCJA NUMIZMATYCZNA
KOMISJI ARCHEOLOGICZNEJ PAN
ODDZIAŁ W KRAKOWIE

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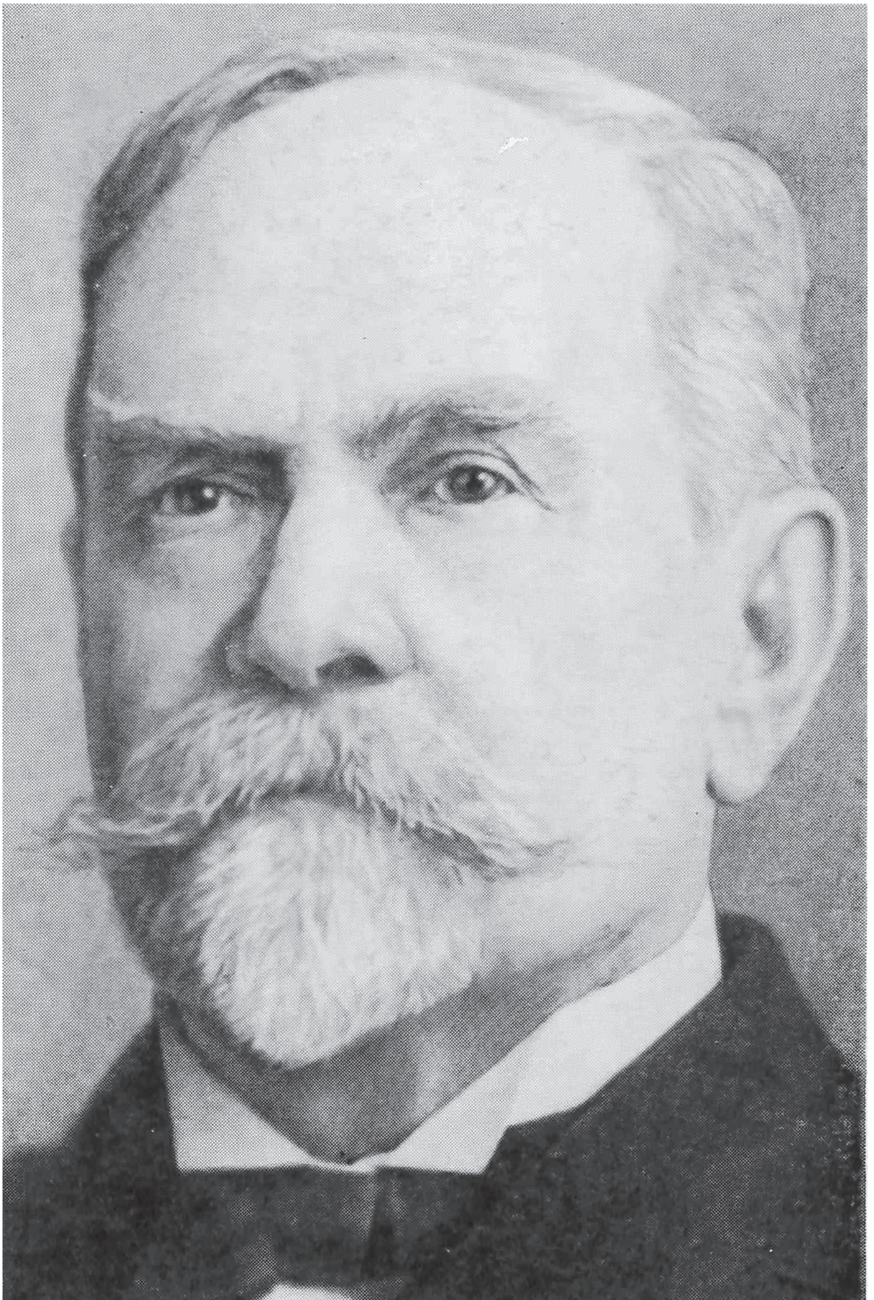

Zygmunt Mineyko (1840–1925). Fot. Archiwum Muzeum Narodowego w Krakowie
Zygmunt Mineyko (1840–1925). Photo: Archives of the National Museum in Krakow

Szanowni Państwo,

oddajemy w Państwa ręce tom XX *Notae Numismaticae – Zapisków Numizmatycznych*. Zgodnie z przyjętymi przez nas zasadami wszystkie teksty publikujemy w językach kongresowych, z angielskimi i polskimi abstraktami. Zawartość obecnego tomu oraz tomy archiwalne są zamieszczone w formie plików PDF na stronie internetowej Muzeum Narodowego w Krakowie (https://mnk.pl/notae-numismaticae-zapiski-numizmatyczne-1). Na stronie dostępne są ponadto wszelkie informacje ogólne o czasopiśmie oraz instrukcje dla autorów i recenzentów.

Sto lat temu 27 grudnia 1925 roku zmarł w Atenach Zygmunt Mineyko (1840–1925), człowiek o niezwykłym życiorysie, oddany Ojczyźnie patriota, weteran Powstania Styczniowego, emigrant, a jednocześnie filhellen i honorowy obywatel Grecji. Jego zasługi na polu walki z rosyjskim zaborcą, emigracyjna tułaczka i wkład w budowę Państwa Greckiego są dosyć dobrze znane, głównie dzięki spisanym przez niego samego pamiętnikom przechowywanym w Bibliotece Jagiellońskiej w Krakowie, w części wydanych drukiem w 1971 roku pod tytułem *Z Tajgi pod Akropol*. Dzięki publikacjom polskich i greckich archeologów znane są również dokonania Mineyki na polu archeologii, a w szczególności jego udział w badaniach na terenie położonego w Epirze słynnego sanktuarium Zeusa w Dodonie.

Zygmunt Mineyko interesował się również numizmatyką i nie były to zainteresowania powierzchowne. Spod jego pióra wyszło – niestety nigdy nieopublikowane – dzieło poświęcone jak sam pisał „objawom numizmatyki". Rękopis tej pracy przechowywany obecnie we Lwowie, w dawnych zbiorach Zakładu Narodowego im. Ossolińskich, pozwala uznać ją za bardzo nowoczesne i wyprzedzające swe czasy opracowanie. Zygmunt Mineyko jest również ściśle powiązany z historią zbiorów numizmatycznych Muzeum Narodowego w Krakowie. W latach 1924 i 1926 do zbiorów krakowskiego Muzeum Narodowego trafiło w dwóch transzach prawie sto antycznych monet podarowanych przez Stanisława Mineykę (1875–1924), syna Zygmunta. Choć formalnie ofiarodawcą był Stanisław najprawdopodobniej inspiratorem daru był jego ojciec, który z powodzeniem realizował ideę wzbogacania polskich instytucji naukowych i muzeów zespołami starożytnych monet. Dary takie zostały lub miały zostać przekazane Muzeum Narodowemu w Warszawie, Uniwersytetowi Wileńskiemu, Uniwersytetowi Jagiellońskiemu oraz jak wspomniano Muzeum Narodowemu w Krakowie. Niniejszy tom naszego czasopisma pragniemy dedykować pamięci Zygmunta i Stanisława Mineyków.

Redakcja

Dear Readers,

We are delighted to present you with volume 20 of *Notae Numismaticae – Zapiski Numizmatyczne*. As is our policy, we publish all texts in the congress languages, with English and Polish abstracts. The contents of current volume and archive numbers are available as PDF files on the website of the National Museum in Krakow (https://mnk.pl/notae-numismaticae- zapiski-numizmatyczne-1). The website also provides all general information about the journal, along with guidelines for authors and reviewers.

One hundred years ago, on 27 December 1925, Zygmunt Mineyko (1840–1925) died in Athens. He was a man with an extraordinary life story, a devoted patriot, a veteran of the January Uprising, an emigrant, and at the same time a philhellene and honorary citizen of Greece. His achievements in the fight against the Russian invader, his wanderings as an emigrant, and his contribution to the building of the Greek state are quite well known, mainly thanks to his memoirs, stored in the Jagiellonian Library in Krakow, some of which were published in 1971 under the title *Z Tajgi pod Akropol* (From the Taiga to the Acropolis). Thanks to publications by Polish and Greek archaeologists, Mineyko's achievements in the field of archaeology are also well known, in particular his participation in research at the famous sanctuary of Zeus in Dodona, located in Epirus.

Zygmunt Mineyko was also interested in numismatics, and this interest was far from superficial. He wrote a work devoted to what he called "the manifestations of numismatics", which, unfortunately, was never published. The manuscript of this work, currently stored in Lviv, in the former collections of the Ossoliński National Institute, allows us to consider it a very modern and ahead-of-its-time study. Zygmunt Mineyko is also closely associated with the history of the numismatic collections of the National Museum in Krakow. In 1924 and 1926, almost a hundred ancient coins donated by Stanisław Mineyko (1875–1924), Zygmunt's son, were added in two tranches to the collection of the National Museum in Krakow. Although Stanisław was formally the donor, it was most likely his father who inspired the donation, as he had successfully implemented the idea of enriching Polish scientific institutions and museums with collections of ancient coins. Such donations were or were to be donated to the National Museum in Warsaw, Vilnius University, the Jagiellonian University in Krakow, and, as mentioned, the National Museum in Krakow. We would like to dedicate this volume to the memory of Zygmunt and Stanisław Mineyko.

The Editors

Tom XX
Kraków 2025

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Comments on the Technology of Production of Krakow Type Staters

ABSTRACT: The subject of this study is an analysis of the technological processes typical for early coinage from the Lesser Poland region, inspired by the Celts. The study focuses on the causes of the under-striking defect in the central part of the reverse of Krakow II type staters. An experiment was conducted on over one hundred samples, examining variables such as the number of strikes, the weight of the sample, and the diameter of the prepared flan. The experiment was carried out on volume equivalents made of tin and on silver samples. The possibility of striking a silver coin on both a cold and a heated blank was tested. The experiment showed that the cause of the defect cannot be attributed to damage or wear of the die.

KEY WORDS: stater of Krakow II type, minting defects, experiment, Celtic coinage, technology

ABSTRAKT: *Uwagi na temat technologii produkcji staterów typu krakowskiego*

Przedmiotem opracowania jest analiza procesów technologicznych typowych dla wczesnych form mennictwa z terenów Małopolski, inspirowanego przez Celtów. Badanie koncentruje się na przyczynach występowania wady niedobicia centralnej partii rewersu staterów krakowskich typu II. Eksperyment przeprowadzono na przeszło stu próbkach, badając zmienne takie jak: ilość uderzeń, masa próbki i średnica przygotowanego krążka. Wykonano go na ekwiwalentach objętościowych z cyny i próbkach srebrnych. Sprawdzono możliwość wybijania monety srebrnej na zimno i na podgrzanym krążku. Eksperyment wykazał, że przyczyn wady nie można wiązać z uszkodzeniem bądź zużyciem stempla.

SŁOWA KLUCZOWE: stater krakowski typu II, wady mennicze, eksperyment, mennictwo celtyckie, technologia

GENERAL AND TECHNICAL NOTES

The minting of coins is a multifaceted process. It requires mastery of numerous technological processes, metallurgical knowledge, and the application of advanced craftsmanship – often of a high artistic standard.[1] In addition, one must take into account the often-overlooked fact that coinage is a form of mass production. It therefore requires advanced organizational planning. To produce coins in ancient times, one needed metalworkers – smelters, casters, and smiths – who provided the tools and materials for future coinage, engravers, whose task was to design the dies, a large group of manual laborers involved in the production of semi-finished products, their cleaning, and distribution within the workshop, and likely weight inspectors involved in the process at various stages of production. The final link in this chain was the mint master and his assistants.

Another factor to consider is the issuer's ability to secure sufficient quantities of precious metal to maintain continuous production over a sufficiently long period. This is linked to the economic and political strength (or stability) of the centers capable of producing coins. Considering the above, it becomes clear that not all peoples of Barbaricum had reached a level at which the production of coinage was even possible. An analysis of the functioning of coins within the spheres defined by culture, politics, religion, and economics far exceeds the scope of this essay; however, it must be noted that their introduction cannot be understood as an act of benevolent innovation. Issuing money is always a costly investment and is intended to serve the issuer's interests, which are not necessarily aligned with those of the user. The imposition of a new product such as money was not always successful. It is impossible to identify clear reasons why approximately half of the Greek city-states did not undertake the production of their own coins. Similarly, we do not know the reasons why Marcomannic coins[2] failed to appear after the

[1] The minting die itself could have been produced in many different ways. One possible method involved creating master dies (so-called "mother dies") with a positive relief. Another technique (applicable for simple designs) involved embossing the design directly onto a thermally softened die using a set of punches, in negative, and then hardening it. It was also possible to combine both techniques. Some researchers suggest that Roman coins may have been produced in this manner, pointing to the difference in the quality of the portrait on the obverse (master die) compared to the images on the reverse and the letters of the legend. This information was presented by Borys Paszkiewicz during a lecture at the 4th lecture session of the Gabinet Numizmatyczny Damian Marciniak (GNDM) on 24 May 2019.

[2] Maroboduus spent about 10–15 years in Rome until 8 BC, receiving an education typical for aristocratic youth; in the opinion of Velleius Paterculus, he "remained a barbarian only by reason of his origin, not due to any lack of refinement or intelligence" (Vell. II, 108). The author additionally attests that Maroboduus gained the patronage of Augustus. It therefore seems evident that he must have understood the benefits of possessing a coinage of his own.

departure of the Celtic issuers from the Bohemian Basin, a region where a rich coinage tradition, developed by the Boii, had previously existed. The emergence of coin issues from Lesser Poland and Kuyavia also remains a mystery. The ability to exchange a portion of metal for goods essential to survival depended on many, often random, circumstances. It is easy to understand the smooth circulation of money when production surpluses appear on the markets. The illusory appeal of money and its physicality can serve as a complement to, and subsequently an alternative for, various types of debt instruments and diverse units of account. Money can serve as a safeguard of livelihood, does not deteriorate during storage, and can be hoarded. In situations of shortages in essential goods in markets or a loss of confidence in weak money, its circulation can only be enforced, for example, by a strong political authority. A thorough analysis of these processes may lead to a revision of often naive notions about the functions of monetary money; however, this goes beyond the scope of this article.[3]

Coin production reached the territory of modern-day Poland through the La Tène culture, likely during the final phase of its existence. The shell staters of the Celtic Boii were probably the direct inspiration. It is highly likely that production was centered on the vicinity of Krakow. This is suggested by Karl Castelin,[4] and, somewhat earlier, by Zenon Woźniak,[5] although, as Marcin Rudnicki notes, “these considerations were more in the nature of scholarly speculation, lacking a clearly defined thesis, which stemmed from the researcher’s own doubts and indecision regarding the location of the mint”.[6] Fragments of typical La Tène molds for portioning metal, originating from Krakow-Nowa Huta-Mogiła,[7] Zakrzów,[8] and Krakow-Nowa Huta-Pleszów,[9] nevertheless clearly point to probable locations. It should be noted, however, that a mint adapted for manual production is mobile, so production could have taken place at any of the indicated locations. Similarly, the production of coins similar to Boian ones[10] in the vicinity of Kalisz (Janków II site) should leave no room for doubt. Fragments of molds and semi-finished products used in coin production were also found there. Also noteworthy is the rich,

[3] David Graeber’s seminal work *Dług. Pierwsze pięć tysięcy lat* (GRAEBER 2017) contains an exceptionally rich body of material on the functions of money, pre-monetary accounting systems, the relationships between markets and money, and the processes of monetization itself.

[4] CASTELIN 1970: 91–96, Tab. 4–5.

[5] WOŹNIAK 1967: 201–231; IDEM 1978: 101–112.

[6] RUDNICKI 2012a: 1–96.

[7] HACHULSKA-LEDWOS 1976: 180–183; HACHULSKA-LEDWOS and WOŹNIAK 1976: 202–206.

[8] MYCIELSKA 1981: 145–151.

[9] KACZANOWSKI 1996: 119–133.

[10] The ⅛ stater coins listed in Paulsen’s catalog under numbers 706–708 and the similar coins 709–710 (PAULSEN 1933) may be the prototypes of the Janków-type coins.

Celtic-inspired coinage of Kuyavia.[11] This activity is associated with the Krusza group of the Przeworsk culture, within whose territory the Claudius Ptolemaeus' Ascaucalis was likely located;[12] however, it is unclear where these coins were produced.

Celtic coinage, or coinage inspired by the Celts from the Polish region, remains a poorly understood subject. In the early 21st century, Polish museum collections contained only six coins attributed to local origins. In 1986, Lesław Morawiecki was able to identify only six numismatic items scattered across Europe with suggested Polish provenance;[13] however, he does not mention the Celtic coin found in Kuyavia around 1905 near Sławęcinek, within the "military training ground"[14] nor the Celtic stater from Masłów. In 1996, a new type of stater found in Kryspinów was added to this collection.[15] At the beginning of the 21st century, the situation is not much better: research in the Kalisz region yielded another 12 coins, including nine of the Kalisz type (Janków II, var. 1).[16] A new coin from Kuyavia has also been discovered at the Gąski 18 site,[17] along with two more obtained from excavations at the site Krusza Zamkowa 3, described as eponymous for the Krusza group of the Przeworsk culture.[18] But since around 2010, there has been an explosive increase in the number of finds. This is linked to the widespread availability of advanced metal detectors. At present, we have information on approximately 200 coins of Polish origin; unfortunately, the vast majority come from illegal searches. Access to this material became possible thanks to the release for study of the archive of Piotr Adamkiewicz, an "amateur archaeologist" and metal detectorist who passed away in 2021.[19]

A characteristic feature of many types of coins issued during the La Tène period is the use of concave-convex dies, as well as the fact that the coins were produced by hand. This applies to nearly all coins issued in Polish territories; the flat-convex coin from Masłów[20] is an exception.[21] Master dies created in relief were used to

[11] ANDRAŁOJĆ and ANDRAŁOJĆ 2012.

[12] COFTA-BRONIEWSKA 1979.

[13] MORAWIECKI 1986.

[14] ZAKRZEWSKI 1928.

[15] KACZANOWSKI 1996.

[16] RUDNICKI et AL. 2009: 103–145.

[17] ANDRAŁOJĆ and ANDRAŁOJĆ 2012.

[18] The rich coinage of Kuyavia, due to its diversity and distinctive character, remains one of the most intriguing and still insufficiently understood phenomena from the turn of the eras in the territory of Poland.

[19] Wioletta Pazowska, speech: "Monety celtyckie z archiwum Piotra Adamkiewicza" [Celtic coins from the archive of Piotr Adamkiewicz], conference Archeologie Barbaru, Brno 25–28 October 2023.

[20] RUDNICKI 2012b: 163–185.

[21] This exceptionally interesting coin features morphological elements that serve as a link between the Krakow type II staters and the Kuyavian Gąski type. However, its flat-convex shape makes it quite difficult to strike, which may indicate a lack of understanding of – or of access to – the tradition of producing Celtic coins with a concave-convex profile.

produce working dies,[22] or the design was developed directly on the working die using a set of punches and gravers. The technique in which master dies are used to produce working dies is certainly more complex, but it allows for the production of multiple working dies operating simultaneously, which may be necessary for large-scale issues.[23]

Celtic coinage is also characterized by a clear process of debasement, primarily linked to the dilution of the coinage alloy. Of course, due to the difference in the specific gravity of gold, silver, or copper, a loss of mass also occurs. It is a matter of debate whether this was caused solely by a shortage of raw materials or was also related to the difference in the nominal value of the individual alloy components, and thus served as a tool for generating profit. In the early stages of the monetization of societies in Barbaricum,[24] it is difficult to argue that such issues were fiat in nature, especially coins issued in Poland, which underwent analogous processes of debasement from gold coins to nominally gold coins. One of the most recent finds of a Krakow-type stater from Opatów also contains a certain amount of copper,[25] which may indicate that these coins evolved toward being minted from substandard coinage alloys. The purpose and justification for minting such coins certainly warrant careful consideration.

Celtic coins are bullion coins. They are primarily minted from gold or silver; their value is determined by their weight and guaranteed by the issuer's mark. Both full-sized coins and their fractions typically bore corresponding marks. These marks were certainly not random; the coin's legitimacy was necessarily reinforced by references to symbols of value significant to its user group. References to symbols associated with religion can be easily identified in Greek, Roman, as well as Celtic coinage. Bronze or potin[26] coins, common in the highly monetized societies of Gaul or among the Eastern group of Celtic coinage, have no counterparts in Celtic-inspired coinage from the Polish territories. North of the Sudetes/Carpathians line, only nominally gold coins were minted. This is significant given that the gold for coin production had to be entirely imported. The typical shape is a more or less regular disc, which is likely due to the metal-portioning technology used. Intentionally oval

22 FOURNIER, FOURNIER and FOURNIER 1989: 119–122; FEUGÈRE 2011: 21–32; ZIEGAUS 2011: 289–299.

23 KIEFERLING 2014: 35–41, Tab. 4–12.

24 The term "Barbaricum" is understood here in a broad sense, as a culturally and ethnically heterogeneous region that stands in relation to a higher culture (Greek, Roman, or even, under certain conditions, La Tène). Similarly, the term "Celticness" need not be strictly tied to an ethnic group; peoples or cultures strongly influenced by La Tène culture may be understood as "Celts".

25 BOCHNAK 2020: 37–47.

26 Potin alloy is a brittle, high-tin bronze (approximately 20% tin). Considering that tin itself was a scarce material in the production of utilitarian bronzes, coins with such a high content of this element can be regarded as a valuable alloying resource.

shapes can also be found (e.g., the Pełczyska type). Quadrangular forms, known for example from the Volcae Tectosages (resulting from striking from metal strips), or irregular forms are not known from the territory of Poland. Coins minted in Poland come in the form of a stater and eight-stater denominations. The ¹⁄₂₄-stater is found exclusively in the vicinity of Kalisz (Janków II type). These observations lead one to accept, with certain reservations, the assumption that coins from the territory of present-day Poland were issued in a system similar to the Boian system.

From the issuer's perspective, a given quantity of metal was intended to produce a strictly defined number of coins. Simple arithmetic determined the weight of the accounting stater, which served as the standard for coin production. The weight of a coin denomination was determined by comparing the weight of scrap metal with a weight standard (stater) or a fraction thereof. It is possible that the weight of smaller denominations was determined by dividing gold or silver wire into specific lengths. Semi-finished products of this type have been found in the vicinity of Kalisz[27] and in Kuyavia.[28] They then had to be remelted in molds, perhaps – as in granule-making techniques – using coal dust to produce spherical pellets. Finds of clay molds from Poland (Zakrzów, Krakow Nowa Huta-Mogiła, Krakow Nowa Huta-Pleszów) do not differ[29] from those from other Celtic minting centers, such as Manching, Stradonice, or Stare Hradisko near Prostějov. The diameter of the indentations is usually about 1 cm, which is sufficient to produce a stater blank.[30] These were used to produce hemispherical pellets of a weight that corresponded to the established weight system, which were then hammered on an anvil into the required shape and size. This factor will be of considerable importance in the subsequent analysis of casting defects.

The prefabricated elements prepared in this way[31] were struck with the issuer's dies. The coins were minted by hand, without the use of guides or any form of

[27] OLĘDZKI, ZIĄBKA and KĘDZIERSKI 2014: 42–50, Tab. 16–17; RUDNICKI et AL. 2009: 103–145.

[28] Although any fragments of fine metal scrap could serve as the basis for various types of production – such as jewelry making – their weight, composition, and the context of other artifacts related to minting activities suggest precisely this use. The balance scales used by ancient minters are not precise enough to reliably weigh portions under 1 gram; perhaps comparing the lengths of wire segments was just as effective, and certainly easier.

[29] The metal-portioning mold found at the Janków II site also does not appear to fit into the Celtic tradition. Its main distinguishing features – a groove down the center and a symmetrical arrangement of indentations – are not found in typical La Tène culture molds. No metal residues were found on the artifact, which may suggest that the object served a different function.

[30] The suggestion found in the literature that the Lesser Poland molds were used to produce smaller ⅛ stater coins (WIRSKA-PARACHONIAK 1981: 153–157) is likely the result of a confusion between surface area and volume measurements. Of course, it is also possible to portion metal to the weight of any lower denomination using the same molds; however, no such coin has been found to date.

[31] A piece of metal hammered into a disc from a hemispherical pellet, known as a "blank" or "flan", is usually round because this is the easiest way to ensure uniform thickness across the entire surface. It is clear that this technology has influenced the shape of coins to this day. In the case of coins struck from sheets of silver (Medieval period and later), it would have been easier – and likely with less waste – to produce rectangular coins.

mechanization. This is indicated by technological and organizational factors. The diameter of the coin for most issues (this dimension is directly proportional to the impact force required to strike the coin legibly) is small, ranging between 0.8 and 2 cm.[32] This parameter appears to be optimal for hand-striking coins without mechanization and, consequently, without a large minting team or a permanent mint location reliant on equipment such as water wheels, stamping hammers, etc. Another argument may be the need for manual and active positioning of concave–convex dies. The convex reverse die has to be pressed at the moment of striking by the mint master in order to prevent the coin from slipping out. Striking is carried out in "two stages": the first, light blow seats the flan centrally in the obverse die, and the subsequent, stronger blow impresses the design. A lack of controlled pressure results, at best, in a double strike. Attempts to use wooden or metal guides for the dies have not yielded satisfactory results; they merely complicate and prolong the process. This is a particularly undesirable phenomenon in the case of hot striking, since the smaller the portion of metal, the faster it cools.

Dies for both the obverse and reverse were often bimetallic – the bronze part with the design was mounted in an iron collar[33] – and the obverse die was sometimes equipped with a spike for mounting in a die block.[34] Purely iron dies were also used. The hoards from Niederaldheim and Kleinsorheim contain precisely such obverse and reverse dies.[35] The preserved dies from Stradonice, Folkusova in Gaul, or Bavaria do not have a geometry regular enough to work with a guide – their shape suggests direct handling by hand. Such guides may be helpful when striking flat coins; they also seem useful when striking large-surface denominations using heavy, e.g., two-handed hammers. We do not know exactly how the dies for the production of the Krakow type coin were constructed.

The depth of hardening with a cold strike, regardless of the degree of surface deformation caused by the impact, is relatively shallow. The forces deforming the flan's surface, according to the formula derived from Newton's second law of motion, are greater the more rapidly the change in momentum occurs. In the case of coins struck by a hammer weighing approximately one kilogram (0.8–1.5 kg), forces most certainly reach values in the range of kilonewtons.[36] Experiments have

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[32] As the surface area of a coin increases, the force required to mint it increases exponentially. The coin's diameter is therefore a compromise between its visual appeal and technological constraints. Coins with a surface area larger than about 3 square centimeters must essentially be struck using a hot-forging process. The increased complexity of production processes may also lead to a larger team of workers.

[33] FEUGÈRE 2011: 21–32.

[34] FURGER-GUNTI 1987: 371–378.

[35] ZIEGAUS 1995; IDEM 2011: 289–299.

[36] In the hands of a skilled coin maker, the hammer's speed can reach 8 to as much as 10 meters per second; meanwhile, the duration of the impact caused by the hammer striking the metal is usually very brief – on the order

shown that it is possible to strike coins with a diameter of less than 2 cm using both hot and cold striking methods when high-purity metal is used. Both processes have their advantages and disadvantages, which become particularly apparent when using alloys with a low precious metal content. In the case of hot coin striking, the required impact force is lower, which results in less die wear and a deeper impression; however, despite achieving a mirror finish due to the surface-level crushing of metal crystals, the coin's surface may appear darker due to surface oxidation during annealing. There is also a risk that defects in the alloy may become apparent, such as inconsistencies, impurities, and so forth. This applies in particular to alloys with a low precious metal content. Hot striking is also more demanding from an organizational standpoint, as the person striking should be assisted by at least two assistants. In the second case, cold striking, the blanks must first undergo a softening heat treatment. Annealing takes place at a temperature of approximately 700–800°C. Within these temperature ranges, it is already possible to assess the temperature based on the color of incandescence.[37] Once this temperature is reached, the material can be cooled and then cleaned if oxides have formed.

Cold striking requires greater impact force due to the higher hardness of the flan, which, in addition to causing die wear, can result in double striking (more strikes mean a higher chance of error), and cracks and chipping may occur due to damage to the crystal lattice; however, it generally produces a coin with a clean, bright, and shiny surface. It is worth noting here that alloys with a lower silver content are harder and less ductile, and after annealing to improve ductility, more undesirable effects may occur if microcracks appeared during the stretching of the pellet to produce the blank.

However, the aesthetic aspect of the coins produced is important.[38] Coins struck less carefully, with minting errors, were common. It should be noted, however, that some minting errors were not regarded as defects at all by the issuers and users of the time. Money retained its value as long as it could be considered to contain the appropriate amount of precious metal. What was perceived as "bad" was mainly – if not exclusively – counterfeit money: subaerati or underweight coins. In hand-

of milliseconds – and depends on the hammer's mass and speed, as well as the physical properties of the metal being shaped.

37 FLOROW 1989.

38 It seems, however, that communities with a longer monetary tradition are more tolerant of coins that are not minted with great care. For groups where coins are a new phenomenon, it seems essential to provide them with stronger legitimacy, for example through references to iconography associated with local sacred symbols or aesthetics in general. It is not difficult to see that a "good" coin should be shiny (to suggest a high metal content), large, heavy, and legible. However, fulfilling all these requirements may prove difficult, too costly, or even unprofitable for the issuer, thereby providing a reason for why some series are scarce or short-lived. Explanations based on a shortage of precious metal are unconvincing insofar as a coin returning to the issuer through circulation can be treated as raw material for subsequent issues.

struck issues, virtually every specimen was, by necessity, unique and differed from others in terms of morphological and metric characteristics. This also applies to specimens struck with the same pair of dies. These errors can be divided into several categories: defects resulting from the material – e.g., cracks caused by the use of an excessively hard alloy (e.g., a coinage alloy with a high copper content), uneven melting, defects resulting from failure to follow technological procedures: excess metal, surface damage, off-center or double strikes, under-striking resulting from insufficient force or improper application of the die, and surface cracks in the coin associated with an improperly conducted metal annealing process. The final category consists of defects resulting from chipping or any other damage to the dies. It is likely that type I Krakow stater coins were struck using chipped dies.[39] It is worth noting here that these "defects" provide the most valuable information about production processes and technology.

EXPERIMENT DESCRIPTION

As part of the outreach activities conducted over the past ten years as part of the Carrodunum Project (Łukasz Kieferling, Hortensja Frankowska, and Kacper Wawrzyniak),[40] dozens of coin replicas have been minted using reconstructed dies. This made it possible to observe a number of phenomena that could later be studied in controlled experiments. One of these concerned the frequently observed under-striking of the reverse side of Krakow II type coins. Coins with a similar defect are known from the collections of the Jagiellonian University Museum and Dresden, and finds from Tuklat and Kunów (nos. 10, 11, 15, 17 in Marcin Rudnicki's catalog),[41] as well as from Opatów.[42] This under-striking has been interpreted as the result of wear on the convex working surface of the reverse die, and indeed such an interpretation seemed logical.[43] This made it possible to observe a number of phenomena; similar errors also appeared on the replicas (Fig. 1), but a visual inspection of the die's condition did not indicate any damage. Subsequent copies, provided that due care was taken, could be struck correctly.

39 RUDNICKI 2012a: 1–96.

40 The set of dies produced by Łukasz Kieferling as part of the Carrodunum Project includes, among others, cup-shaped staters: Krakow types II A and II C, the Vindelici Kellner IX B (KELLNER 1990), and the Kuyavian Gąski and Sławęcinek types (ANDRAŁOJĆ and ANDRAŁOJĆ 2012), a flat-convex stater from Masłów (RUDNICKI 2012b), and flat coins (Totfalu-type drachma, Vagiones quinarius). Each of these coins is characterized by different minting features, depending on size, profile, or surface relief.

41 RUDNICKI 2012a: 1–96; BUL 2022: 43–74.

42 BOCHNAK 2020: 37–47.

43 This interpretation is suggested, among others, by Łukasz Bul in his study on Krakow-type staters (BUL 2022: 43–74).

When analyzing the possible causes of under-striking, it was necessary to limit the number of variables. Several factors influence the final appearance of a hand-struck coin. The size of the dies can of course be excluded, as this is a fixed value for the entire issue. The first factor is the force of the strike – or, more precisely, the cumulative force resulting from the number of strikes: the greater the force, the larger the resulting coin will be. The second is the volume of metal used. The third factor is the ratio of the coin blank's size to the die's size. Additional factors, though difficult to verify, may include the issuer's expectations regarding the coin's aesthetics or the efficiency of the minting team; these factors could not be taken into account.

Krakow II type coins, chosen for this experiment, vary in weight (5.1–7.42 g), dimensions (16–19 mm), and alloy composition, and thus in their malleability. In a first step, the alloy composition to be used was decided upon. For practical and economic reasons, the use of silver coins was abandoned. The high softness of the tin used corresponds to some extent with the malleability of heated silver.[44] Approximately 0.5 kg of tin with a small amount of lead was melted down and then divided into hemispherical ingots using a tray coin mold. Investigating the effect of the mass of the different blanks on the depth and legibility of the impression seemed the most obvious approach, given that group II A staters are struck quite carefully; errors are typical of later, lighter subtypes with a lower gold content. For this reason, all experiments were conducted using the same pair of dies for the Krakow stater of type II C (Fig. 2). However, testing semi-finished products of varying weights did not provide the answers we were looking for. The assumption that thicker, higher-volume samples would produce a more complete and distinct impression was not confirmed. Experiments conducted to examine the effect of force or the number of strikes on larger samples, however, led to interesting observations. While it is true that as the applied energy increased, the central part of the coin became slightly deeper, when the flan extended beyond the edge of the die, it flattened against it and deformed, leaving an under-struck center. Applying more force could even result in pieces of metal breaking off. It should be noted that this type of process is more time-consuming and exhausting, and the result is not worth the effort.

Standardizing the sample weight was the next step. The weight was fixed based on the lightest Krakow-type coins, which were made of 5.2 g of silver. The equivalent volume in the substitute material (Sn) is a portion weighing approximately 3.6 g.

[44] The yield strength of tin is about 15 MPa. For annealed (cold) silver, it is approximately 70 MPa at room temperature. Heating the metal can significantly reduce this value, effectively to zero at the melting point. Within the temperature range of 650–800°C – i.e., a range that an experienced metallurgist can easily estimate based on the color and brightness of incandescence – the value for many metals drops to below 20% of its original level. For silver, this would therefore be around 14 MPa. These values are, of course, dependent on the composition of the alloy.

At this stage, the variable under investigation was the diameter (Fig. 3) of the semi-finished product. Of the approximately 120 samples prepared for testing, metal pieces ranging in diameter from 10 mm (unflattened pellets) to flans as large as some 20 mm were used. Additionally, impressions were made on metal flans cut from a sheet of metal with a diameter of 18 mm and a thickness of 1.5 mm (Fig. 4). With a reverse die diameter of 17 mm, this represented approximately 60–120% of its size. In the case of blanks larger than 100%, under-striking occurred virtually regularly. Cases of full striking were rare; however, it has not been possible to determine conclusively whether this was related to the angle at which the die was applied, the specific position of the blank between the dies, or some other factors. At the minimum values for the blank's diameter, the design was complete and sharp; however, despite repeated striking with the die, the coin might not reach the intended diameter.

Since the experiment was conducted on a material with a lower density than silver – and thus lower recrystallization temperatures – the sample did not harden significantly during striking. If silver had been used, the hardening resulting from the crushing of the metal's crystalline structure[45] would have prevented it from being struck properly.[46] In the case of using silver, work hardening resulting from the deformation of the metal's crystalline structure would have prevented it from being properly struck. For coins the size of a Krakow stater (approximately 17 mm), "cold striking" is possible, but prior annealing of the material is necessary. While it is reasonable to assume that after being hammered to the desired diameter, the blanks could have been reheated and cleaned in charcoal, it is difficult to accept that the same process could have taken place during the actual striking of the coin. Precise repositioning of the coin between the obverse and reverse dies can be difficult and time-consuming, and usually results in double or multiple impressions; it is only possible when the metal is cold. Consequently, tests were also conducted on four 4.5 g and one 5 g portion of silver (Fig. 5). The lower weight compared to the original coins was due to the fact that Krakow coins contain an admixture of gold. This metal has a specific gravity of 19.3 g/cm³, nearly twice as dense as silver, so even a small percentage in the alloy composition significantly increases the sample's mass. The specifications allow for the coin to be struck either cold or hot from blanks as large as approximately 90% of the coin's size and subjected to annealing to increase ductility.

[45] FLOROW 1989.

[46] The recrystallization temperature for most metals is about 30–60% of their melting temperature. It is also inversely proportional to the degree of prior deformation (cold work). For low-melting metals, recrystallization may occur at room temperature.

Tests conducted on a material similar to the original yielded further insights. First, no significant change in the metal's ductility was observed depending on whether the blank was placed on the die at a temperature of approximately 700°C[47] or at room temperature. It also became possible to assess the quality of the coin's strike based on the sound made by the die. Because the die must be pressed down firmly during striking, there is a risk of burns, and this also makes it difficult to control. An incorrect angle when applying the reverse die increases the risk of the coin "escaping" from between the dies, creating an additional fire hazard. This, of course, applies to concave-convex coins with smooth obverses,[48] and the Krakow stater series II C-D falls into this category.

Sample I tested the feasibility of cold striking a coin. The process involved preparing a pellet, hammering it down to the specified diameter, annealing the blank to soften it, and finally striking the coin. The blank was stretched to approximately 14–15 mm, which, based on previous findings, should have ensured a clean strike. Indeed, the coin struck cleanly, but it did not reach its full dimensions. The number of strikes was also significant; about 8–10 strikes (Fig. 6), each of which required checking the die's position to avoid defects associated with double striking, made the process energy-intensive and time-consuming.

Sample II, weighing 5 g, was prepared in the same manner, with the exception that the blank was placed on the die at a temperature of approximately 650–700°C. It still took 5 strikes to strike it. However, reducing the number of strikes by half was not a significant improvement, as the coin stopped stretching after the third or fourth strike. This was indicated by the clear, high-pitched sound emitted by the die. In the next stage, the number of strikes was reduced to two. Samples were prepared with the following diameters: IV 15–16 mm and V 14–15 mm. Both were struck while hot. The result was coins that looked very similar, with indentations in the center and on the "crescent" that were identical in character to those found on the original coins. After two strikes, the coins increased in diameter by about a millimeter. In the case of both specimens, after heating and repositioning them between the dies, it would certainly have been possible to achieve a complete deep cold strike (precise positioning of a hot coin between the dies is impossible under the conditions of a reconstructed mint). The effectiveness of this method has been confirmed by the results of Sample V (Fig. 9) and previous productions of copies

[47] The approximate temperature values used are based on the fact that the blank cools rapidly when placed on the obverse die. The same applies to the estimation of other process parameters, as the process should be completed as quickly as possible. Similarly, hand-flattened blanks are never geometrically perfect circles.

[48] An interesting and unique solution to this problem appeared on some (late?) Kuyavian staters from Piotr Adamkiewicz's archive. The smooth obverses retained a pair of ridges ending in small balls. Their placement almost at the very edge of the die suggests that they should not be associated with any symbolic representation, but rather with technological factors.

for museums or private collectors, which required the creation of perfect master coins. It is doubtful, however, whether such a process could have been used in the production of original coins. The production of a single specimen took over a minute, which is an unacceptable amount of time for mass production.

The study conducted appears to have identified the causes of the shallow relief on the reverses of Krakow II type coins (Figs. 7–8). The hypothesis that it was caused by die wear or damage, based on a visual assessment of under-struck specimens, cannot be sustained. Similarly, suggestions that the specimens were worn as a result of prolonged circulation should likely be treated with caution. Although the workshop (or workshops?) producing Krakow II type coins struck the coins quite carefully,[49] a precise estimation of the flan size is quite difficult in full-scale production. The coin does not lose much in terms of legibility or aesthetic value if the flattened disc fits within the die's recess. In terms of fully reproducing the die design, this could be considered a flaw; however, given the number of surviving specimens with this defect, it clearly did not pose a problem for the issuers. The original premise of the experiment was production using heated blanks. It was assumed that cold striking, due to the greater hardness of the material, might lead to under-striking; however, this assumption did not hold true to the extent expected. The key factors turned out to be the ratio of the prepared blank's diameter to the diameter of the obverse die's recess and the number of strikes. An important factor also appears to be the loss of mass in the later series of Krakow staters, which favored the rapid cooling of the flan when placed onto the die. After the experiment was completed, all coins struck from silver were marked with a "COPY" countermark.

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[49] It is difficult to attribute such meticulousness to the Kuyavian workshops or to the issuer (or issuers?) of the Kryspinów type coins. An example is the Gąski type stater from Modlniczka (BYRSKA-FUDALI, PRZYBYŁA and RUDNICKI 2009). However, this is a supra-regional phenomenon and appears to depend mainly on the issuer's aesthetic preferences.

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PLATE 1	Fig. 1. Selection of specimens with distinct under-striking; the arrow points to a specimen struck from a punched disc
PLATE 2	Fig. 2. Replica of the Krakow stater II C dies used in the experiment Fig. 3. Mint blanks: A. prepared blanks measuring 60–120% of the die size; B. a disc cut with a punch; C. a replica coin; D. portioned metal
PLATE 3	Fig. 4. Material prepared for the experiment Fig. 5. Micro-issue in silver; the arrows indicate under-struck areas
PLATE 4	Fig. 6. Coins from top: struck with a single blow (blank approximately 14 mm), below struck with 2–3 blows (blank approximately 14 mm), and struck from an unstretched portion (6–8 blows) Fig. 7. Close-ups of the surface. Arrows indicate the undamaged surface of the blank; hammer and anvil marks in the under-struck area may suggest die damage
PLATE 5	Fig. 8. Result of using large blanks (approximately 100–120% of die size): cut on the edge of the die (photo on the left); 2 under-striking of the center and a "crescent" (photo on the right). The top photo shows the result of striking from a flan 18/1.5 mm in diameter Fig. 9. Coins with a diameter of 17 mm (100%) struck from blanks approximately 80% (A) and approximately 100% (B) the size of the die Photos by Ł. Kieferling

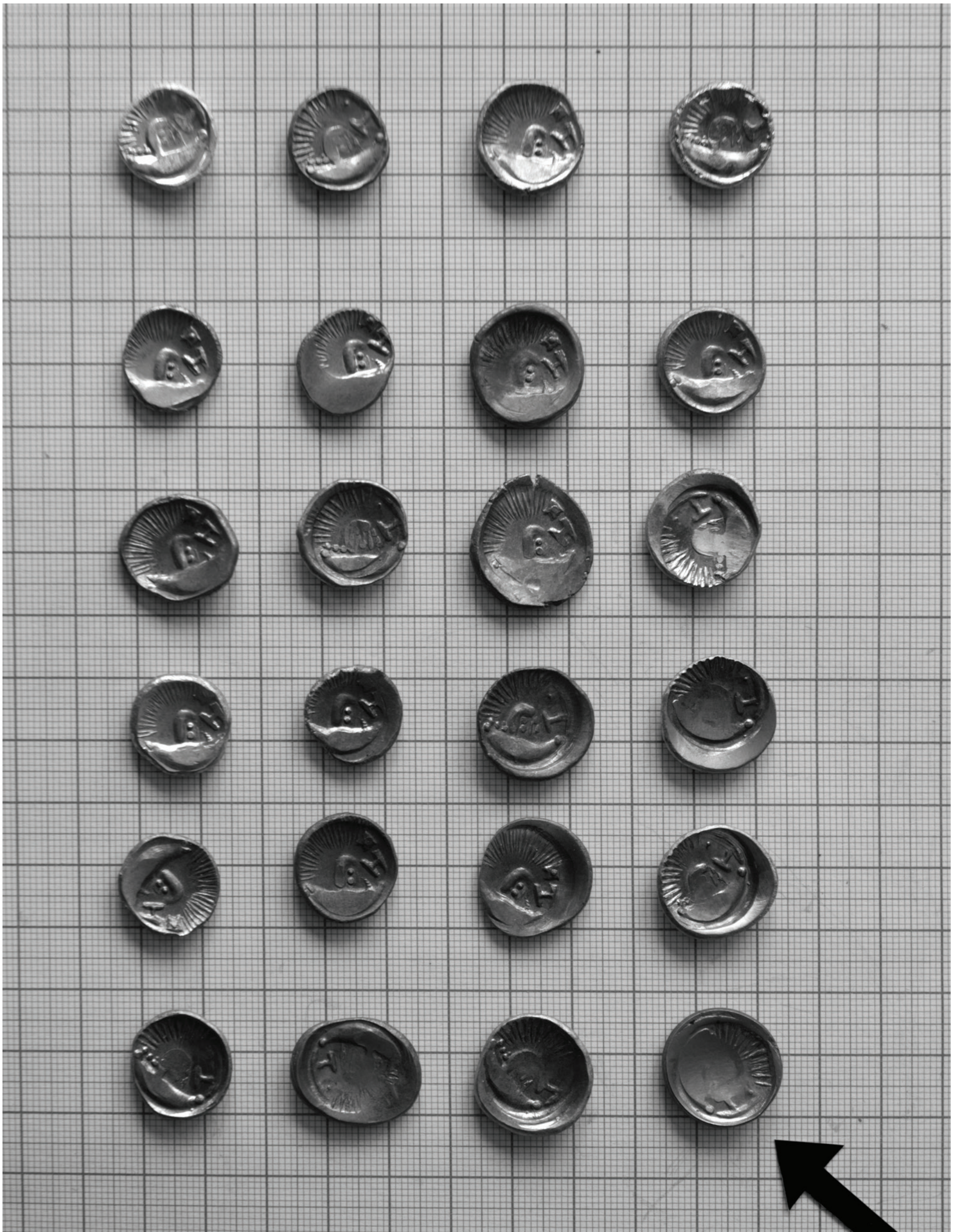


Fig. 1

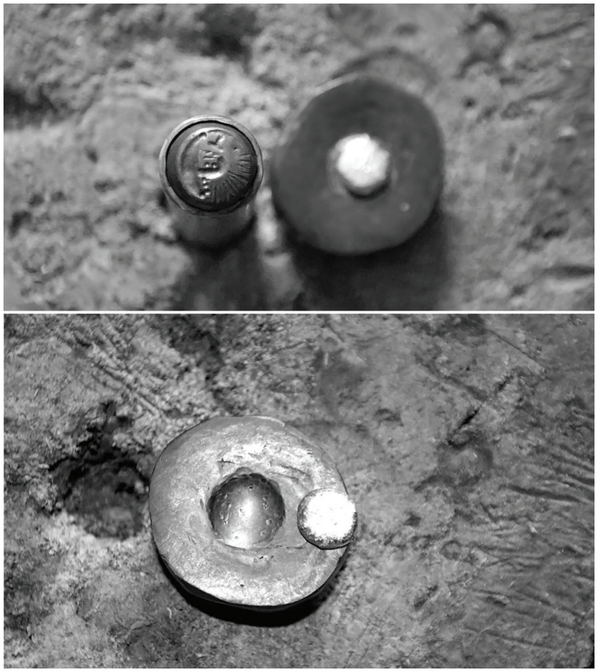


Fig. 2

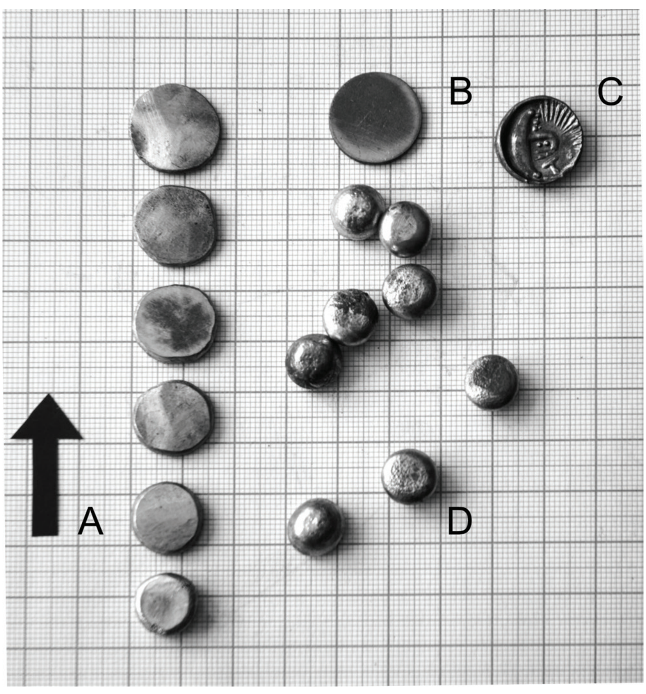
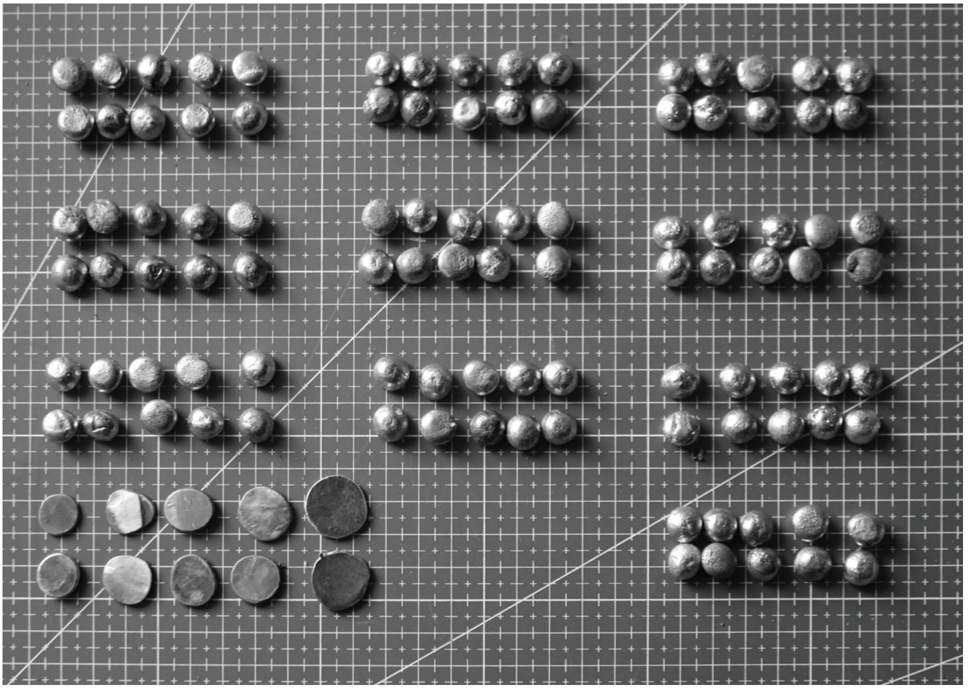


Fig. 3



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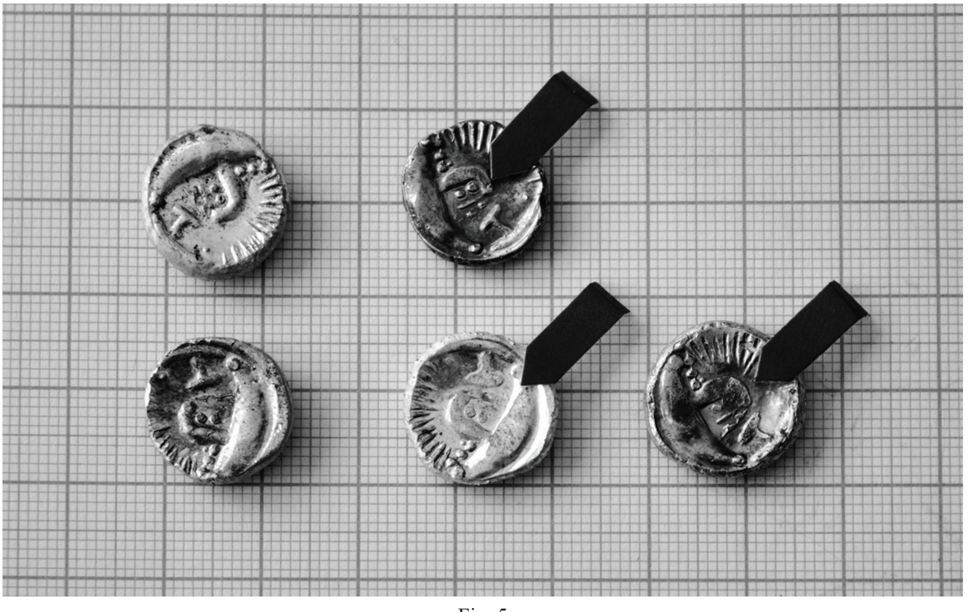

Fig. 5

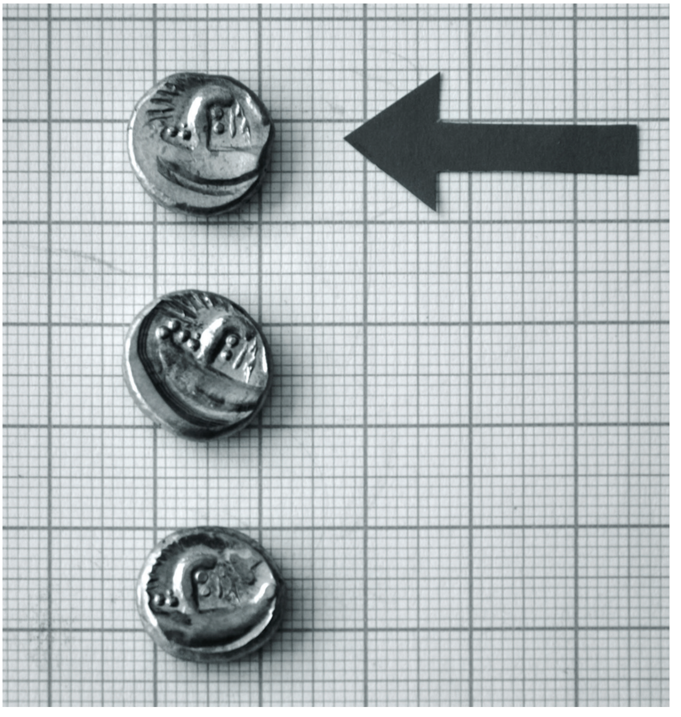

Fig. 6

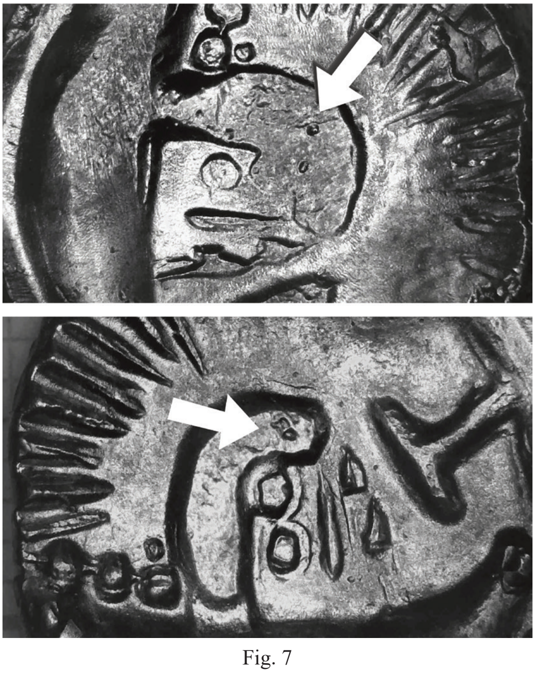

Fig. 7

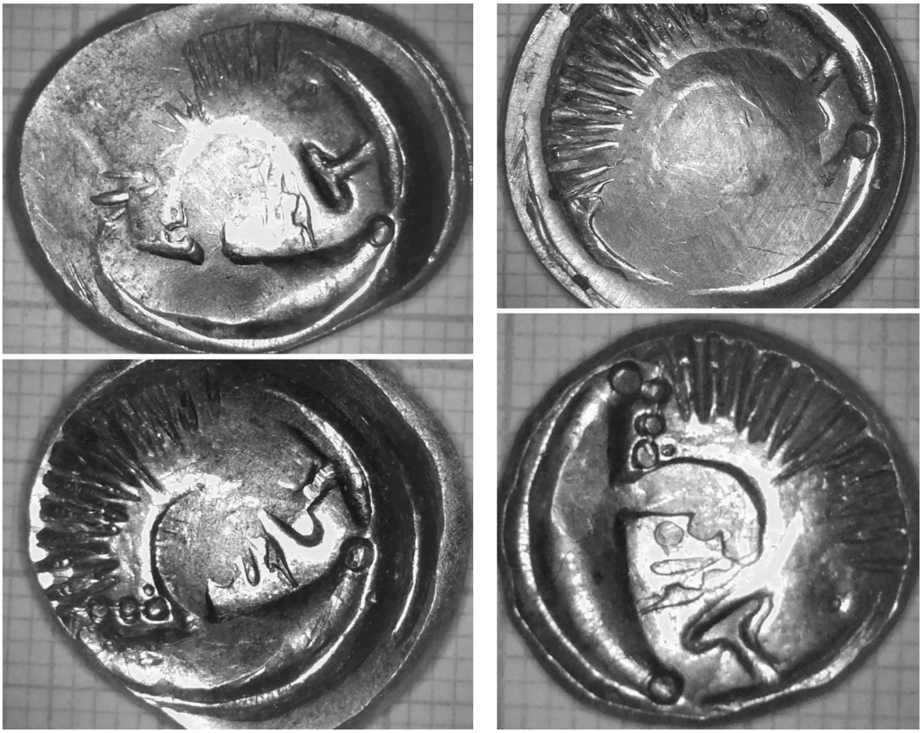

Fig. 8

Fig. 9