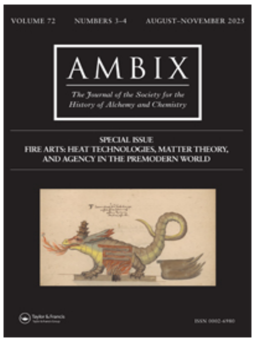

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Rounding Up: Undertaking Experiential Research on Granulation Techniques in a Charcoal-Fired Furnace

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This paper describes a programme of practice research that combines historical technology (small charcoal-fired furnaces) with contemporary digital making methodologies (digital CNC milling). The intention was to create small spherical granules of precious metal suitable for granulation, an ancient metalworking technique. The authors begin by providing an overview of granulation's historical background and the different traditional methods used to create granules. They give an account of the equipment used in the physical experiments and describe the rationale behind specific design decisions. In particular, they reflect on the nature and properties of producing a reducing atmosphere inside the firing chamber of the furnace, and the relevance of this to the granulation process. They detail the digital making methodologies that were used to create setters made from graphite to encourage the formation of perfectly spherical granules, and how these relate to recent developments of the technique by contemporary makers. The project is a case study that demonstrates how practical reflexive experimentation can broaden our understanding of unrecorded but crucial skills such as fire management and that practising such skills in conjunction with digital methods of making can offer new insights into past technologies and processes.

Introduction

Granulation – the application of tiny metal granules to a surface for decorative effect – is an important technique in both modern and historical goldsmithing. First emerging in ancient Mesopotamia and spreading through Eurasia, it has

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been found in numerous cultures across the millennia, and it has recently gained increasing attention from contemporary artists worldwide.

Granulation is also a challenging technique, as it requires the production of large numbers of spheres with smooth, clean surfaces. While contemporary makers have developed a few different methods to achieve this (described below), each has its advantages and drawbacks, and makers must weigh carefully the need for quantity over the quality of the final finish. In an effort to improve fabrication, we looked to combine contemporary technology and historical sources to explore the limits of the materials and processes and to develop new approaches. From the outset, then, this was not intended to be a typical historical investigation. The work combined modern and historical practices in ways not done by historians or makers, but this synthesis revealed surprising insights into the history of the process as well as providing future directions for contemporary making.

The programme of experimentation produced results with important consequences for areas far beyond contemporary craft practices: it yielded insights about granules and granulation in general, with consequences for archaeology, anthropology, and art history; but it also yielded insights about fire-based practices – with consequences for understanding modern and historical fire management and furnaces. Finally, it is significant for considering the relationship between material exploration and historical reconstruction, and their relevance beyond the history of science: the experiential insights of the reconstruction inform modern-day making and craft practices, showing how historical research can be mobilised beyond its disciplinary boundaries.

This article presents the findings on granule production and shows the relevance of this seemingly narrow technique to larger historical and technological issues. By looking past the final product to the processes of granule production in a reducing atmosphere, we make explicit the different ways of using fire and the subtle and not-so-subtle effects of different heat sources, thereby expanding our understanding of fire as a material and a technology, and prompting deeper consideration of its agency. Therefore, although not a traditional historical reconstruction, our work still provides insights into materials and processes that can be of value to historians, archaeologists, anthropologists, and makers, and it suggests ways that interdisciplinary research can further historical scholarship, at the very least by generating new sets of questions.

Our practical experiments focused on two objectives. The first objective was to explore whether it was possible to utilise a charcoal-fired furnace, built on site by Peter Oakley for the Fire Arts Symposium for experiments in cupellation, to also undertake a series of experiments with fine silver granulation. Of prime concern was the question of whether the furnace could reach and maintain the temperatures needed to effect the formation of granules, and whether the reducing atmosphere inside the furnace would be useful in producing the perfectly smooth, unoxidised finish usually only achieved by bench-top methods of granule production. The rare possibility to experiment with creating and maintaining a high temperature, reducing atmosphere through fire management techniques made this a unique opportunity for experiential knowledge generation, especially considering that charcoal-fired furnaces have largely been replaced with electric ones in the contemporary jewellery workshop. The second objective revolved more specifically around improving ancient techniques of granulation with contemporary digital manufacturing methods, building on the research conducted by David Huycke.[1] Based on these two objectives, Katharina Vones formulated a set of research questions that considered historical aspects of the technique and responded to contemporary methodologies for mass granule production in electrical kilns proposed more recently.

The overall process of granulation can be divided into three stages: (1) the production of the granules; (2) the placement and temporary gluing of the granules onto a two – or three-dimensional backing structure, and (3) the permanent fixation of each granule to the backing.[2] This tripartite sequence applies to both historical instances and contemporary practice.[3] The motivation to develop methods that produce a large number of granules simultaneously is rooted in the fact that much of the visual language of granulation as a technique has traditionally depended on its visual opulence. To achieve this, masses of miniscule granules are arranged in clusters or patterns and affixed to a thin backing sheet.[4] Utilising the least amount of surface contact between the backing material and each tiny sphere to maintain its visual discreteness creates a desirable three-dimensionality and "liveliness" that is often lacking in granulated areas that have been flooded with solder.[5]

As will be shown below, the quest to develop methods that enable granule production en masse has been an essential part of the conversation around this technique. As each stage – including the creation of the granules – can be achieved by applying different methods, scholars have disagreed over which techniques were used to create specific historical examples. This has led to heated debates among scholars in the fields of archaeology, archaeometallurgy, and art history.[6] It also

1 David Huycke, "Decorative and Structural Granulation in Larger Silver Artefacts," in *Proceedings of the Santa Fe Symposium on Jewelry Manufacturing Technology* (Albuquerque, NM: Rio Grande, 2022), 287–310; David Huycke, *The Metamorphic Ornament: Re-thinking Granulation: A Research into the Transformation Possibilities of Granulation into Sculptural Silverworks* (Hasselt: Hasselt University, 2010).

2 This division is proposed by both Jochem Wolters, *Die Granulation: Geschichte und Technik einer alten Goldschmiedekunst* (Munich: Callwey, 1983); Marc Rosenberg, "Abteilung: Granulation," in *Geschichte der Goldschmiedekunst auf Technischer Grundlage*, vol. 3. (Frankfurt: Verlag Von Heinrich Keller, 1918), 1–158.

3 Jeanette K. Caines, "Granulation Demystified," in *Proceedings of the Santa Fe Symposium on Jewelry Manufacturing Technology* (Albuquerque, NM: Rio Grande, 2016), 123–42.

4 A comprehensive guide to nearly all possible aesthetic typologies of granulation has been compiled in Wolters, *Die Granulation*, 15–23.

5 Rosenberg, "Abteilung: Granulation," 8–20.

6 Diane Lee Carroll, "A Classification for Granulation in Ancient Metalwork," *American Journal of Archaeology* 78, no. 1 (1974): 33–39; Diane Lee Carroll, "On Granulation in Ancient Metalwork," *American Journal of Archaeology* 87, no. 4 (1983): 551–54; Paolo Parrini, Edilberto Formigli and Emilio Mello, "Etruscan Granulation: Analysis of Orientalizing Jewelry from Marsiliana d'Albegna," *American Journal of Archaeology* 86, no. 1 (1982): 118–21; Daniea Ferro, Vania Virgili, Adelia Carraro, Edilberto Formigli, and Lorenzo Costantini, "A Multi-Analytical Approach for the Identification of Technological Processes in Ancient Jewellery," *ArchéoSciences* 33 (December 2009): 51–57; Maria Filomena Guerra and Thilo Rehren, *Authentication and Analysis of Goldwork* (Rennes: Presses Universitaires de Rennes et ArcheoSciences, 2009); Rosenberg, "Abteilung: Granulation", 1–158; Jochem Wolters, "The Ancient Craft of Granulation: A Re-Assessment of Established Concepts," *Gold Bulletin* 14 (1981): 119–29.

means that the kind of material exploration undertaken here can provide insights that could aid in assessing such arguments.

Hypotheses about historical granulation techniques have been based on different types of evidence, and some researchers, such as Nestler and Formigli, have made use of historical furnace reconstruction to support their proposals.[7] However, this was not the aim of the experiments presented in this article. The lack of definitive evidence regarding how granules were typically created for granulation meant any experimental reconstruction of the process had to be speculative. We therefore chose modern methods of production and materials where these appeared to be the most appropriate and practical solution as part of an overall viable working process which could then test previous researchers' claims and expectations (a similar approach can be found by Vilarigues et al. in their work on enamelling in this special issue). Our aim was to develop a way of making the finished product that followed the core principles of historical granulation manufacture but included space for innovation, rather than to attempt a more purist "re-enactment" methodology. For instance, the production of a highly reducing atmosphere inside the muffle chamber was the main focus for the granulation experiments: whether we stimulated the fire by using modern tools, such as an electric blower, rather than the more traditional bellows was a secondary concern. As Nestler and Formigli aptly comment, "ultimately, it is important to remember that both the ancient and the modern methods are two aspects of the same discipline. What we learn from the ancients shouldn't be used to imitate their forms, but should be creatively reused."[8]

Such a methodology follows the proposal made by Fors, Principe, and Sibum that experimental reconstructions of alchemical and historical scientific processes should start by reproducing the key principles of the process and then incrementally move towards a more total reproduction.[9] Granting ourselves the licence to be innovative with the process brought an additional benefit: the freedom to challenge conventional wisdom through practical experimentation. This would help determine if commonly assumed barriers really were immutable or just the result of conventions of modern studio or laboratory practice.[10] When conducting the granulation tests, we wanted to concentrate on identifying the impact of the redox potential of the atmosphere in the charcoal-fired furnace, thereby putting this aspect of heat technologies in the foreground. Utilising new digital methods to create setters from a modern material (graphite in block form) facilitated these

7 Gerhard Nestler and Edilberto Formigli, *Etruscan Granulation: An Ancient Art of Goldsmithing* (Brunswick, ME: Brynmorgen Press, 2010).

8 Nestler and Formigli, *Etruscan Granulation*, 87.

9 Hjalmar Fors, Lawrence M. Principe, and Otto Sibum, "From the Library to the Laboratory and Back Again: Experiment as a Tool for Historians of Science," *Ambix* 63 (2016): 85–97.

10 For a description of a comparable programme of experimentation that challenged entrenched beliefs about historic glass formulations, see Ian Hankey, "Working with Venetian Style Glass," virtual lecture posted 24 September 2015, by The Bard Graduate Center in New York City, You tube, https://www.youtube.com/watch?v=sSBY6Lc2-hU (accessed 6 October 2025).

experiments by providing quickly observable and definite results working with set parameters (the accuracy of the size of the indents in the graphite blocks).

The RELLIS Automated Fabrication & Design Lab proved to be an ideal location to undertake the practice-led experiments, providing a health – and safety-compliant, well-ventilated outdoor space that was sheltered from the elements to construct the charcoal-fired furnace. It also had all the amenities of a fully equipped digital fabrication facility close at hand, allowing for the swift, in-situ modification of tooling and building materials, as well as providing extra technical support when needed.

Starting with a historical survey of how granulation was used in jewellery and artefacts since its origination in ancient Mesopotamia, the following sections detail the schedule of experiments undertaken during the Fire Arts workshop in 2023, with a particular focus on how fire management techniques and the application of digital making methodologies played an essential part in shaping the experiments.

Granulation past and present

Granulation represents one of humanity's most ancient decorative goldsmithing techniques, with the first documented examples having been found in the tombs of Ur, dating back as far as 2500 BCE.[11] Details of three distinct phases of its early geographical spread and subsequent establishment in the decorative vocabulary of artifacts have been identified. According to Wolters, the first phase took place during the age of archaic advanced civilisations and is closely tied to recurring diasporas within the geographical regions surrounding the Mediterranean and Black Seas due to political upheavals.[12] One such example is the dispersal of Sumerian craftspeople after the plundering of Ur by the Eastern Canaanites in 2019 BCE that led to the proliferation of the technique in Syria,[13] but the more general migration of skilled artisans along established trade routes also contributed significantly to the spread of the technique, for instance to Greece (including Crete), Troy (in what is now modern-day Turkey), Egypt, Palestine, Iran, and finally also more northern regions such as Georgia and Armenia.[14] In this, parallels can be found between the migration of alloys and other metalworking techniques from the Mediterranean regions northwards and through the steppes of Eurasia, subsequently reaching China, Korea and Japan.[15]

This initial phase lasted until approximately the end of the second millennium BCE, at which point granulation as a technique fell out of favour and was largely

11 Christine Lilyquist, "Granulation and Glass: Chronological and Stylistic Investigations at Selected Sites, ca. 2500–1400 BCE," *Bulletin of the American Schools of Oriental Research* 290, no. 1 (1993): 29–94.

12 Wolters, *Die Granulation,* 67.

13 Wolters, *Die Granulation*, 68–69.

14 Rosenberg, "Abteilung: Granulation," 28–31; Lilyquist, "Granulation and Glass," 33–34; Rosenberg, "Abteilung: Granulation," 25–27; Wolters, *Die Granulation,* 86–87.

15 Natalia Shishlina and Anastasia Loboda, "Metalworking Techniques on the Eurasian Steppes in the Late Bronze Age: Technical Analysis of the Borodino Treasure Spearheads," *Oxford Journal of Archaeology* 38, No. 4 (2019): 420–42; Emilia Ferraro, Sandra Wilson, and Katharina Vones, "Metalwork in the Andes and Japan: A Comparative Study," *Silver Studies* 38 (2022): 98–107.

FIGURE 1 Gold sanguisuga-type fibula (safety pin) with patterns in granulation, seventh century BCE, courtesy of the Metropolitan Museum of Art, New York. Original Available at: https://www.metmuseum.org/art/collection/search/253339.

forgotten until the archaic period around 800 BCE, when it regained popularity and began a second phase of geographical expansion (lasting roughly until 600 CE). Initially, granulation experienced a revival in Greece, and was subsequently dispersed through the Greek and Phoenician colonisation of the Eastern and Western Mediterranean.[16] The technique was adopted by the Etruscans by the end of the seventh century BCE, who are widely recognised as having refined its artistic expression, by reducing the size of individual granules into the realm of the miniscule, sometimes achieving up to 100 granules per square-centimetre, and producing works of exceptional complexity and high aesthetic value.[17] Still showing stylistic influences of Greek granulation designs, the Etruscans developed their own distinctive interpretation of the technique, which focused on fine linear granulation in the northern regions of Italy (Figure 1) and figurative massed granulation in the south (Figure 2).[18]

Objects that were adorned in such a fashion included not only items of jewellery (fibulas, brooches, necklaces, earrings, beads, and rings), but also functional objects such as boxes, cups, bowls, combs, and ceremonial swords. During the classical period, granulation also spread from Palestine throughout the Roman Empire and later the Holy Roman Empire, with Greek influences continuing to dictate aesthetic conventions (Figure 3), but it was not widely practiced by Roman goldsmiths in Italian territories, and never reached the heights of Etruscan works.[19] Significant for this period however is the wide geographical spread achieved within the Holy Roman Empire (Figure 4) and

16 Rosenberg, "Abteilung: Granulation", 70–78.
17 See Parrini, Formigli, Mello, "Etruscan Granulation," 119–21; Wolters, *Die Granulation*, 79–83; Carroll, "On Granulation in Ancient Metalwork," 552–54
18 Wolters, *Die Granulation*, 79–83.
19 See Wolters, *Die Granulation*, 83–87; Rosenberg, "Abteilung: Granulation," 85–86.

FIGURE 2 Gold serpentine fibula (safety pin) with animals in massed granulation, seventh century BCE, courtesy of the Metropolitan Museum of Art, New York. Original Available at: https://www.metmuseum.org/art/collection/search/245958.

FIGURE 3 Gold earring with clustered spheres and pyramidal granulation, Roman, second – third century CE. Note the significantly simplified style of decorative granulation in comparison to earlier examples. Courtesy of the Metropolitan Museum of Art, New York. Original Available at: https://www.metmuseum.org/art/collection/search/44767.

then neighbouring territories, which reached as far north as Hungary, southern Russia, and England.[20]

The "Lost" technique of granulation

There is a well-rehearsed narrative of granulation as an ancient "lost technique" that fell from favour due to changes in production methods caused by technological advances, only to be "rediscovered" during the eighteenth and nineteenth centuries

20 Rosenberg, "Abteilung: Granulation," 87–90.

FIGURE 4 Gold Brooch with extensive granulation, Ottonian, 970–1030 CE. Courtesy of the Metropolitan Museum of Art, New York. Original Available at: https://www.metmuseum.org/art/collection/search/465119.

FIGURE 5 One from a pair of gold ear ornaments (Prakaravapra Kundala), India, first century BCE – first century CE. Courtesy of the Metropolitan Museum of Art, New York. Original Available at: https://www.metmuseum.org/art/collection/search/39320.

by prestigious goldsmiths, such as members of the Castellani family who wanted to emulate the works of antiquity.[21] This Eurocentric perspective, however, ignores the continued practice of granulation in territories mostly belonging to the third phase of expansion outlined by Wolters that commenced in the first century BCE and included China, India (Figure 5), Korea, and South America.[22] As an outlier, Iran (Figure 6) is particularly significant in this respect, as it represents one of the few regions alongside Mongolia, Tibet, Russia and Hungary in which granulation

[21] Nestler and Formigli, *Etruscan Granulation,* 21; Susan Weber Soros and Stefanie Walker, *Castellani and Italian Archaeological Jewelry* (Yale, CT: Yale University Press, 2004).

[22] Wolters, *Die Granulation*, 83–87; Emma C. Bunker, "Gold in the Ancient Chinese World: A Cultural Puzzle," *Artibus Asiae* 53, no. 1/2 (1993): 27–50; Yong Shi, Yadi Wen, Xiaojun Li, Zhaojian Liu, Yumin Huang, and Bei He, "Transmission and Innovation on Gold Granulation: The Application of Tin for Soldering Techniques in Ancient China," *Heritage Science* 10, no. 1 (December 2022): 122; Panpan Tan, Cuimin Zhang, and Junchang Yang, "Scientific Analysis on Gold Belt Buckle with Dragon Pattern from the Han Tomb of Yingchengzi, Dalian (大连营城子汉墓出土龙纹金带扣的科学分析与研究)," *Archaeology* 12 (2019): 106–15; Fan Yang, Thilo Rehren, Ping Kang, Siran Liu, and Kunlong Chen, "On the Soldering Techniques of Gold Objects from the Boma Site, Xinjiang, China," *Journal of Archaeological Science: Reports* 33 (October 2020): 102572; Panpan Tan, Ming Li, Xiaojuan Huang, and Junchang Yang, "Technique and Utilisation: Characterisation of Copper Granulation during the Sui and Tang Dynasties (581–907 CE)," *Journal of Archaeological Science: Reports* 62 (2025): 105000.

FIGURE 6 Detail of gold hair ornament with a fine example of decorative elements made of a single granule seated inside a ring of wire, Iran, twelfth to thirteenth century CE. Courtesy of the Metropolitan Museum of Art, New York. Original Available at: https://www.metmuseum.org/art/collection/search/451113.

has been proven to have been continuously practised from around 1600 BCE until well into the nineteenth century CE.[23]

While granulation is consistently regarded as a rarefied goldsmithing technique practised only by craftspeople of the highest skill levels, the production of granules themselves is much more widespread.[24] Not only is it a stage in smelting, refining, or alloying, but the resulting metallic spheres can be of interest to wide-ranging audiences. In early modern Europe, for instance, lead shot became increasingly prevalent as battlefield munition, making the production of granules an ever more important issue for rulers and their military concerns, as the example of the Redcliffe "shot tower" demonstrates.[25] Coarse granules were, and still are, used to this day in smelting and alloying processes, but their irregular shape sets them apart from the granules produced for the purpose of decorative granulation.

Due to these wider applications, it is unsurprising to find methods for creating granules in early modern metallurgical treatises. Both Gregorius Agricola's *De Re Metallica* and Lazarus Ercker's *Beschreibung allerfürnemisten mineralischen Ertzt und Berckwercksarten* present methods for pouring molten metal that would result in many tiny spheres.[26] Ercker (1528–1594) advises pouring the metal through a broom into a receptacle filled with water, while Agricola (1494–1555) identifies new birch twigs or straw as possible stirring tools. Agricola also describes an alternative method: pouring the molten metal onto a large, submerged stone to break up the stream of metal. Pouring techniques were also employed in

23 Wolters, *Die Granulation*, 72.
24 Rosenberg, "Abteilung: Granulation," 4–5.
25 John Mosse, "Redcliff Shot Tower," *BIAS: Bristol Industrial Archaeological Society Journal* 2 (1969): 4–5; Walter Minchinton, "The Shot Tower," *American Heritage of Invention & Technology* 6, no. 1 (1990): 52–55.
26 Herbert Clark Hoover and Lou Henry Hoover, *De Re Metallica* (New York: Dover Publications, 1950); Anneliese Grünhaldt Sisco and Cyril Stanley Smith, *Lazarus Ercker's Treatise on Ores and Assaying* (Chicago, IL: University of Chicago Press, 1951).

FIGURE 7 Golden Box-form ornament with granulation and filigree, Egypt, sixth to fourth century BCE. Courtesy of the Metropolitan Museum of Art, New York. Original Available at: https://www.metmuseum.org/art/collection/search/551317.

subsequent centuries to create lead shot. Especially in the seventeenth and eighteenth centuries, many military armoury complexes had "shot towers" built, ranging from forty-two to over eighty metres tall, to enable molten lead to be dropped from high enough to produce standard-sized lead spheres, which were needed as ammunition for muskets. Though it involved the significant financial outlay of building a tower, the pouring method was much more efficient, both in terms of volume production and finish, than the alternative of casting lead in spherical moulds.[27] A similar method was described in 1823 as having been used for granulation, leading to the creation of a "granulation machine": this consisted of a four-foot-high water barrel that was used to catch granules generated by a set of ever-faster rotating drums into which molten metal was poured with a spoon or a ladle.[28] These examples expose the deep connection between the extensive material knowledge necessary to exploit the inherent physical qualities of metal in the production of perfectly spherical granules reliably, repeatably, and at scale.

Wolters argues that early historical accounts do not present granulation as a discrete technique because ancient goldsmiths regarded it to be an inherent part of a wider decorative vocabulary used to decorate the surface of three-dimensional metal forms.[29] In support of Wolters's claim, extant examples (Figure 7) confirm that spherical granules have frequently been used in combination with fine wire work (filigree). Also compelling is Marc Rosenberg's argument that filigree as a technique was more common and associated with artefacts found at all skill levels within the "folk crafts" and that granulation was a courtly art form generally only practised by goldsmiths with the highest skill and reputation to flex their artistic muscles.[30] Expanding this theoretical narrative could link the disappearance

[27] Trevor C. Lipscombe and Carl E. Mungan, "The Physics of Shot Towers," *The Physics Teacher* 50 (2012): 217–20; Minchinton, "The Shot Tower," 52–55.

[28] Rosenberg, "Abteilung: Granulation," 10.

[29] Wolters, *Die Granulation*, 34–36.

[30] Rosenberg, "Abteilung: Granulation," 4.

of granulation from Europe as coinciding with changes in courtly cultures of making and the associated networks of workshops, where skilled craftsmen exchanged practical knowledge and created precious objects for a cultured audience with highly refined tastes. Such historical arguments are intriguing and warrant further examination.

Granule production: methodologies of fire management

The method of granule production devised by Katharina Vones during the experiments was derived from both historical and contemporary sources. The historical methods described in this section are still practised today by a handful of contemporary practitioners who specialise in granulation. These include techniques using charcoal-filled crucibles inside a kiln, or bench-top methods.[31] Contemporary makers have also developed some completely novel or hybrid approaches, such as the one suggested by Huycke.[32] Each method has benefits and drawbacks, relating to the surface finish on the granules and the scale of production, and considerations of this range of limitations and affordances were influential in developing the methodology proposed in this paper.

While it is possible to produce individual granules at the jeweller's bench using a charcoal block and blow torch, this is a laborious process. Wolters claims that the use of an open charcoal fire in conjunction with a blowpipe of some sort would have been the most likely method used by ancient metalworkers.[33] He believes this would be the most feasible way to achieve the temperatures necessary for both the manufacturing and the fusing of the granules. However, from a practical standpoint, not only would manufacturing granules in the quantities required have been incredibly time consuming, but it would also have required highly advanced and consistently applied skill in controlling a blowpipe. While the method may have been used to create small batches of granules, it is difficult to believe it would have been practical to produce enough granules to decorate more complex pieces, especially in the minuscule size ranges utilised in Etruscan artefacts, some of which are below optical visibility.

In considering which historically documented processes can create large numbers of granules, there are two candidates: first, the bench-top metal-pouring method; second, the use of a charcoal-filled crucible in a furnace. The first combines the physical principles of surface tension and gravity to deliver perfect metallic spheres, while the second requires only a constant heat source, which could be open or enclosed. The practical experiments described in this paper have demonstrated the feasibility of achieving and maintaining the same temperatures using a

[31] Oppi Untracht, *Jewelry Concepts & Technology* (London: Robert Hale Ltd., 1982); Wolters, *Die Granulation*, 45–50; Panpan Tan, Junchang Yang, and Juan Ji. "Experimental Simulation of the Ancient Production of Gold Granules," *Heritage Science* 12, no. 1 (2024): 1–12; John E. Cogswell, *Sterling Silver Granulation* (New York: State University of New York College at New Paltz, 1984); Caines, "Granulation Demystified," 123–42.

[32] Huycke, *The Metamorphic Ornament,* 55 ff; Huycke, "Decorative and Structural Granulation," 297–301.

[33] Wolters, *Die Granulation*, 46–48.

relatively simple charcoal-fired furnace, as do the experiments conducted by Nestler and Formigli.[34]

Variations of the metal-pouring method are described in great detail by Wolters, who suggests that a water bath was frequently used in conjunction with other tools, such as a sieve, to break up the stream of molten metal.[35] A small handheld broom could also have been used to agitate the water and encourage the formation of uniformly spherical granules in larger quantities as also previously described by Agricola.[36] Recent archaeometallurgical research undertaken by Tan, Yang, and Ji has shown that the metal pouring method is less reliable and more wasteful than the crucible method, due to its propensity to create gold flakes (rather than spherical granules) through splashing when the molten metal impacts surfaces of the container.[37] It is therefore a less likely candidate for granule production in contexts where the conservation of scarce material resources was paramount.

More recently, John Cogswell has described a granulation technique he developed, employing both a charcoal block and water, which he has termed the "Free Fall Method."[38] In this approach, a charcoal block is suspended about twelve inches above a bowl of water at an angle. Single pieces of metal are subsequently placed on the block and melted with a hand-held torch until they roll off the block into the bowl of water.

The alternative to the pouring method is the crucible method. This involves heating a small refractory crucible filled with alternating layers of charcoal powder and small fragments of precious metal to a temperature above the metal's melting point. Agricola refers to this process in *De Re Metallica* as the first stage of purifying silver.[39] The material used can be sheet metal cut into pallions (small squares or rectangles), wire cut into short lengths, filings, shavings, or even dust. This makes it a very frugal method of granule production, where waste materials from other processes in the jewellery workshop can be reused. Using pallions or jump rings made from wire has a distinct advantage: if each piece is identical, this will give a standardised final granule size. However, in practice the crucible method typically produces a range of variably sized grains, as molten metal fragments close to each other tend to agglomerate into larger granules (Figure 8). The crucible method also imparts particular surface markings to the granules; these differ from those made using the blowtorch and charcoal block or pouring methods.[40] Contemporary practitioners have claimed that varying the provenance of the silver also produces variations; for instance, Caines asserts

[34] Nestler and Formigli, *Etruscan Granulation*, 81 ff.
[35] Wolters, *Die Granulation*, 45–46.
[36] Hoover and Hoover, *De Re Metallica*, 447.
[37] Tan, Yang, and Ji, "Experimental Simulation of the Ancient Production of Gold Granules," 5.
[38] John E. Cogswell, "Sterling Granulation," in *Metals Technic: A Collection of Techniques for Metalsmiths*, ed. Tim McCreight (Brunswick, ME.: Brynmorgen Press, 1992): 3–15
[39] Hoover and Hoover, *De Re Metallica*, 448.
[40] Tan, Yang, and Ji, "Experimental Simulation of the Ancient Production of Gold Granules," 6–8.

FIGURE 8 Experiments with the traditional charcoal layering technique undertaken as part of the Fire Arts Symposium. Note the variation in size of granules despite starting with wire jump rings of equal size, and partial melting of some fragments. Courtesy of Katharina Vones, 2023.

that using rings made from commercial grade wire results in more “wrinkled” surface textures than granules made from pallions.[41]

In the latest iteration of the technique, Huycke has developed a method which combines the volume production of the crucible method with improved reliability regarding granule sizing.[42] He has achieved this by using bespoke ceramic tiles that act as setters and fit inside a crucible. Each tile is covered with indentations that have a ledge halfway down and a rounded floor. The ledge is for the metal pallions to rest on, while the rounded floor helps the metal form and retain the shape of a perfect sphere once it has melted. After loading each indentation with a pallion, the tile is placed inside a crucible, covered with a layer of paper, and the crucible is filled with ground charcoal. Multiple crucibles can be placed inside an electric kiln for a single firing, enabling the production of large volumes of granules.

Superior surface characteristics through a reducing atmosphere

Perfectly spherical granules with a smooth surface are the most desirable outcome of the production stage. However, a range of environmental and physical factors can make this aim difficult to achieve through the commonly used historical processes. Each of the methods described above embodies a different approach to our understanding of fire management and the way in which heat is applied to metal in order to liquefy it. For instance, the bench-top method, even when using the most simplistic tools of a basic blowpipe and a charcoal block, tends to produce the most perfectly shaped granules with excellent surface characteristics.

41 Caines, “Granulation Demystified,” 126.
42 Huycke, *The Metamorphic Ornament,* 97ff.

This is partly due to the skill of the craftsperson to apply the heat of the flame just long enough to melt the metal, let it contract into a perfect sphere, and then remove the flame immediately to set the sphere's shape. Leaving the heat on the spherical granule for too long leads to the molten silver absorbing oxygen, which is released again as it solidifies. If the interior of the granule remains molten too long after a surface skin of solid silver has formed, the metal is prone either to "spitting" or to excessive porosity. This manifests as pitting on the surface of the spheres and as small cavities spread throughout the metal, including just below the surface, necessitating heavy polishing to seal them when they become exposed. The use of a charcoal block as the work surface is meant to counteract oxidisation by producing a locally reducing atmosphere. Even Huycke's innovative contemporary technique, which partly relies on a locally reducing atmosphere achieved through the addition of charcoal powder to his custom setters, produces granules that, while perfectly spherical, require extensive post-processing to achieve the ideal highly polished finish.[43]

Based on the knowledge of these methods and the importance of mediating atmospheric conditions through the addition of charcoal, Vones's first research question focused on the ability of the charcoal-fired furnace to produce a strongly reducing atmosphere and how this can enable the creation of granules with surface characteristics superior to those produced within the non-reducing environment of modern electrical kilns. Granulation makes these processes visible and expands our understanding of the different types of heat and fire. Practical experimental reconstructions undertaken by Nestler and Formigli using furnaces based on ancient Egyptian drawings of metalsmithing workshops, provided the starting point for the experiments undertaken in this paper.[44] In considering the advantages and limitations of the test furnaces they constructed to make the granules, one factor they identified as important was the inherent tendency of charcoal to produce a heavily reducing atmosphere when burnt in a confined space. They conducted successful experiments in their experimental kilns of both granulation and soldering techniques.

While historically granules with diameters up to around 2 mm were regarded as the largest achievable size, Huycke's process allowed him to push the maximum granule size to approximately 3.2 mm. This brings us to the second of Vones's research questions: whether it is possible, with the aid of contemporary digital fabrication technologies, to create precise, CNC-milled setters that could expand the size of uniform granules up to a diameter of 6 mm. Though it was anticipated that gravity would compromise the formation of totally spherical granules of this size, even with the additional support of the setters, the intention was to identify the diameter at which the granules would display the characteristic "mushroom" deformation if all other factors were optimised. It was also decided to conduct tests at

[43] Huycke, "Decorative and Structural Granulation," 301.
[44] Nestler and Formigli, *Etruscan Granulation*, 81ff.

smaller diameters between 1 and 3 mm to test the process at sizes that had previously been reliably achieved by others.

Why use a charcoal-fired furnace?

As noted above, Huycke states the maximum viable granule diameter that can be created using his process as 3.2 mm.[45] But this is, in part, due to restrictions imposed by the electric kiln, which necessitates rapidly ramping up the temperature inside the firing chamber and a long cool-down period. The presence of an oxidising atmosphere and this type of firing cycle means Huycke's granules require finishing, despite the offsetting effect that the addition of charcoal powder has.[46] The presence of oxygen causes multiple problems as it leads to the creation of a layer of silver oxide on the granules as well as the pitting described above.

In contrast to furnaces powered by electricity, the charcoal-fired furnaces used for the granulation tests here have a tendency to produce a reducing atmosphere in their inner chamber where the tests are placed (called the muffle chamber). This is due to a combination of factors.

First, the firing chamber is filled with combustible carbon. The limiting factors for the firing are the amount of air (and therefore oxygen) flowing through the firing chamber and the ambient heat in the firing chamber. As the carbon is in excess, carbon monoxide, a reducing molecule, is formed in abundance in the fire chamber whenever the flow of air is even slightly restricted, especially once the ambient working temperature of around 1000°C is reached.

Second, if the design of the muffle chamber includes vents in its walls to improve the speed of heat exchange from the fire chamber into the muffle chamber, carbon monoxide can also flood the muffle chamber whenever the mouth of the chamber is closed. Contemporary muffles are much lower and wider than historical designs, and they are made with relatively thick walls, floor, and roof, using a very alumina rich refractory body. Such muffles would not be able to withstand the thermal shock they would receive if used in a charcoal-fired furnace. We thus built bespoke muffles for the test furnace using a contemporary clay body with a composition close to that described by Ercker, which is used for the production of contemporary refractory elements.[47] Their profile was determined by the size of the muffle mouth; their closest historical references are illustrations found in *De Re Metallica*.[48] For some processes such as cupellation, it is necessary to keep a sufficiently oxidising atmosphere in the muffle chamber. This is achieved by allowing a small amount of air to flow into the chamber through the mouth.[49] But for processes where one wants to exclude oxygen to stop its absorption by the

45 Huycke, *The Metamorphic Ornament*, 99.
46 Huycke, "Decorative and Structural Granulation," 301.
47 See Peter Oakley, "Fire Management in Practice: Building and Managing Charcoal Fired Assay Furnaces as Experimental Reconstructions" (this special issue).
48 Hoover and Hoover, *De Re Metallica*, 228.
49 See Peter Oakley, "Fire Management in Practice".

molten metal – and to keep the metal from oxidising when red hot – maintaining a reducing atmosphere by completely closing off the chamber is preferable.

The configuration of the charcoal-fired muffle furnace confers an additional advantage. The drop in the temperature of the muffle chamber that results from opening the mouth of the muffle can be exploited. The initial temperature drop that occurs can be used to freeze the metal, and the setter can then be immediately removed from the furnace. This results in the granules undergoing a crash cooling. The swift withdrawal of the heat source promotes the creation of granules with smoother surface characteristics and a rounder profile, due to the metal solidifying almost immediately. This creates similar conditions to those present in the benchtop methods discussed in detail above, but with the added advantage of producing a multitude of granules in one batch as with other kiln-based methods. The use of bigger setters could easily multiply this advantage, while eliminating the need for extensive polishing, as experienced by Huycke.[50] Adding the vents meant that when the mouth of the muffle was closed again after removing the saggar, the atmosphere inside the muffle chamber also returned more quickly to reducing. We therefore kept the muffle mouth closed as much as possible during the granulation tests; we believe this had a significant positive effect on the results.

Cutting the graphite setters needed to create the granules

Using information gathered from the sources identified above, a set of granule setters was designed using computer aided design (CAD) software and digitally fabricated out of a block of graphite using a Roland CNC milling machine (Figure 9).

This method of setter manufacture differs from that of Huycke, who uses a customised punch to make multiple impressions in blocks of clay which are then fired before use. Huycke's approach requires a large amount of upfront effort in the production of each new punch to produce a different sized granule. In addition, the processes of indenting and firing the clay inevitably introduce differences in the size of the indents, resulting in possible variations in the size.

In contrast, solid blocks of graphite were chosen as the medium for the setters used in our series of tests. High quality engineering graphite is an easily millable material that can be cut to very fine tolerances. Graphite requires no finishing; it can be used directly after being milled. In a reducing atmosphere, the graphite should remain stable; this contrasts with an oxidising furnace, where a graphite block would be quickly eroded as the surface converts into carbon dioxide.

Utilising this digital production method and graphite as the medium enabled the direct creation of setters with precise forms and repeatable tolerances. Using CAD to design the setters and CNC milling to cut them meant the form of each indentation could include high-resolution details. For example, the ledges that the metal

50 Huycke, *The Metamorphic Ornament,* 103–05; Huycke, "Decorative and Structural Granulation," 301.

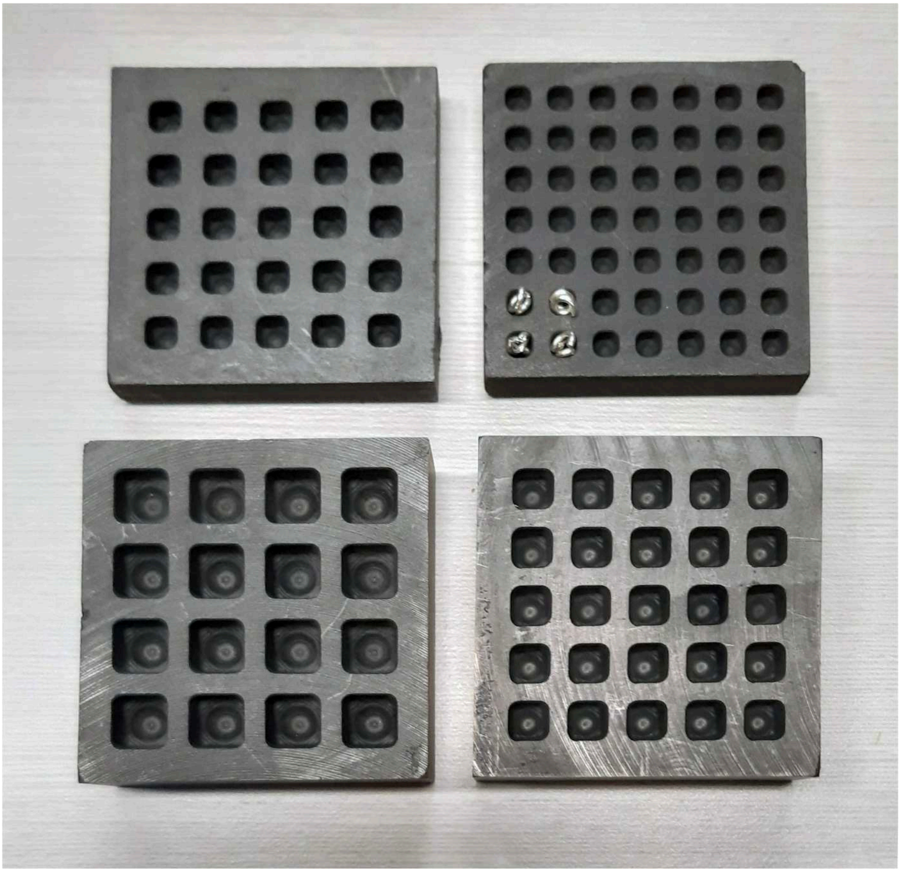

FIGURE 9 The initial set of graphite setters, ranging from 3 mm to 6 mm, counterclockwise. Courtesy of Katharina Vones, 2023.

rested on were created with rounded edges. This feature allowed the melting silver to slide more easily into the rounded divots (Figure 10) without snagging.

Using CAD software meant it was also possible to quickly change the cutting settings, enabling the milling machine to change the scale of the indents without any additional cost. Initially, CAD designs were drawn up for setters with indentations starting at 2 mm and increasing in 1 mm-increments to 6 mm. This design flexibility had other potential benefits. It facilitated any later iterative adjustments and could be used to manufacture an unlimited number of identical setters in the sizes matching the successful tests.

Reconsidering and redesigning the saggars

It was decided that the graphite setters would be placed in refractory containers – called *saggars* – to help reduce corrosion from oxidation and to physically protect the setters when being inserted or removed from the furnace. For the first tests,

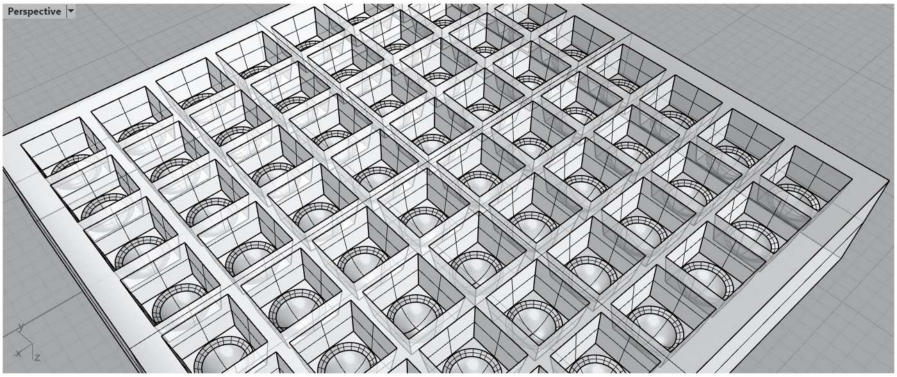

FIGURE 10 CAD drawing of first iteration of 4 mm setters, produced in Rhino 6. Courtesy of Katharina Vones, 2023.

FIGURE 11 The 5 mm graphite setter fully loaded with Britannia silver jump rings inside the alumina crucible used during the first set of experiments. Note the difficulty in fitting the appropriate amount of silver into the divots. Courtesy of Katharina Vones, 2023.

industrially manufactured alumina rectangular crucibles that fit the muffle were used as saggars (Figure 11). Two crucibles were used for each setter; these were placed mouth-to-mouth on top of each other to form a closed shell. Having closed saggars would also keep the silver covered and thus free from incidental fly ash landing on top.

While alumina crucibles are made to withstand temperatures of up to 1750°C, during the firing cycle of the 5 mm granules in the furnace (20 min at 961°C), the upper crucible partially melted and collapsed onto the setter, leading to complete failure of the structural integrity of the spherical granules during their liquid stage. Other alumina crucibles also showed signs of cracking. While created to withstand high temperatures, the alumina refractories are too brittle to

FIGURE 12 The cooling station assembled from loose firebricks. Courtesy of Katharina Vones, 2023.

withstand the thermal shock associated with being placed in, or removed from, the charcoal furnace. The latter was partially resolved by building a cooling chamber from insulation bricks (Figure 12). However, for later tests, bespoke lidded saggars made of industrial crank clay were used. These proved to be much more resilient; nevertheless, crack formation could be observed in this material as well after a number of firing cycles.

In one of the concluding tests, a crank setter base was used without a lid. After the firing, the graphite block was found to have been slightly eroded by oxidation. This was evident as a roughening of surface and slight rounding of the corners. The effect was minimal, and the surface of the silver remained unoxidised, but over multiple firings the setter would have been more significantly damaged, eventually compromising its functionality. We also tried using saggars with lids and filling the space in between the setter and the wall of the lower saggar with powdered charcoal to act as sacrificial material. As a powder it would have a larger surface-area-to-volume ratio and thus be more prone to oxidation than either the metal or the setter if any oxygen were present. This would enhance the reducing atmosphere inside the saggar and further protect the graphite. Setters fired with charcoal powder in the saggar showed no sign of erosion. This practice – using saggars with a lid and adding charcoal powder around the setter – was therefore adopted as the standard practice for firings.

The redesign of the saggars did have one negative consequence. The walls of the new saggars made from industrial crank clay were thicker than the old alumina ones. This made the saggars slightly larger and more difficult to manoeuvre in and out of the muffle chamber. In particular, it proved difficult to get the arms of the tongs around both sides of the saggar, as the saggar had to be close to both walls of the muffle. Consequently, a new furnace tool was needed that could hook the saggar from above and pull it onto a steel spatula for removal.

The temporality and phenomenology of fire management

The most demanding aspect of the charcoal-fired furnace was the lead time it required before the first test could be run. As with all technologies dependent on an external, solid-fuel heat source, the operator has to monitor and manage the fire during the time it takes to bring the chamber to operating temperature. This is an inherent disadvantage compared to technical systems using electricity or internal combustion.[51] In the case of the charcoal-fired test furnace, the pre-testing preparation period took between one and a half and two and a half hours. The possible variation resulted from multiple factors: slightly damp charcoal or kindling, high atmospheric humidity, or a cold furnace could all delay the fire catching and establishing itself. A dry, breezy day, dry kindling and charcoal, and a furnace still warm from use the day before helped the fire establish more quickly.

Once the graphite setters had been prepared and loaded with silver jump rings (for an example of this see Figure 11), they were carefully placed inside a saggar and transported to the furnace, where they were placed on a ledge inside the cowl for gentle pre-heating. When the pyrometer read a temperature of around 1000°C, the piece of insulating brick covering the opening of the muffle was removed and the saggar swiftly inserted into the muffle, using a combination of a long-handled enamelling spatula and a pair of cast-iron tongs. This sequence had an air of urgency, as a delay between removing the fire brick blocking the muffle's mouth and replacing it could cause the temperature in the chamber to drop by 100°C. Though this could all be performed by one person, working as a team of two, with one person removing and replacing the brick, and the other extracting the test and transferring it to the cooling chamber, proved the most practical option. It was surprisingly easy to fall into a spontaneous routine when managing this process of extraction and insertion, with movements resembling a carefully choregraphed dance of handling tools and hot surfaces to complete the sequence as smoothly and swiftly as possible. Placing tools and implements in determined locations near the furnace played a pivotal role in these interactions. As Ingar Brinck observes:

> The arrangement of tools and materials in physical space indicates a temporal order and mode of procedure. […] Epistemic actions can change the course of events and the outcome of making in one single move. Consequently, they play an indispensable role for the quality and efficiency of performance. Often performed absentmindedly, they stay one step ahead of conscious deliberation and verbal reflection that are notoriously slow.[52]

The notion of embodied knowledge as enabling an intuitive and ritualistic engagement with fire as a material through the efficient operation of the furnace is

[51] James Alfred Ewing, *The Steam Engine and Other Heat-Engines* (Cambridge: Cambridge University Press, 1910), 585–638.

[52] Ingar Brinck, "Craft Thinking: A Relational Approach to Making and Design," in *Craft and Design Practice from an Embodied Perspective,* ed. Nithikul Nimkulrat and Camilla Groth, 1st edn (Oxford: Routledge, 2024), 30–40.

essential for understanding the temporalities at play during the experiments. The fact that the firing cycles of the furnace reached their peak efficiency beginning two and a half hours after being started meant that the least fuel-consuming way of working was to run the furnace for at least six hours and prepare all samples in advance, placing the loaded saggars in close proximity to the tools and implements. During such working days, the lead operator became the servant of the furnace, constantly watching its behaviour for signs of decline in efficiency and attentively catering to its needs. Perceiving the volatile nature of fire by closely observing its ebbs and flows prompted the authors to treat it as a living entity. This was reinforced through the language used to describe it: the fire is fed, grows, and settles; it can choke, and it will eventually die.

The phenomenological aspect of perceiving and interacting with fire as a living material also included reading the furnace's ongoing condition through visual, aural, olfactory, and haptic clues; smelling and seeing the wisps of smoke after lighting to confirm the fire had caught, before the flames were evident; later watching the condition of the flames and glow of the charcoal to assess the draft; and, at top temperature, assessing the colour of the muffle's walls and saggars, which give a strong indication of the temperature in the chamber. How to correlate the radiant colour observed with degrees centigrade is described in detail by Shepard and Deitrich in a comprehensive table, and harks back to historical goldsmithing and other heat-based practices, where this type of visual analysis and experiential learning is the only way to reliably predict a material's temperature without technical measuring instruments.[53] This embodied method of temperature determination can be highly accurate. A test of the traditional charcoal-filled crucible method of granulation undertaken in the Quimbaya furnace (also being tested at the Fire Arts workshop) (Figure 13), relied entirely on this method, as did other experiments in this furnace, as discussed by Vélez-Posada and Jiménez in this special issue. Although we took direct Celsius measurements for our granulation tests in the charcoal-fired furnace using a pyrometer, the colour of the fire radiating from the inside of the muffle, as well as that of the metal when it was removed from the furnace, provided reliable visual cues as to temperature. Using the pyrometer was done, in part, to provide data on the ambient atmospheric temperature during the tests for publication and replication purposes. But having the instrument also made us aware of more subtle fluctuations that are not easily visually identified, including the typical hundred-degree drop in the ambient temperature of the muffle chamber when the front was opened.

As the graphite setters were enclosed in the saggars, it was not usually possible to observe the process of the silver melting and forming spherical granules. However, the experiments with the open saggar did prove promising in this regard. If the cover of the muffle mouth were fitted with a mica window, it would be possible to observe the point at which the silver melted, while simultaneously monitoring

[53] Orson Cutler Shepard and Waldmar F. Deitrich, *Fire Assaying* (New York: MacGraw-Hill Inc., 1940).

FIGURE 13 A spontaneous granulation test undertaken in the Quimbaya furnace. The slipping charcoal as it descended in the Quimbaya tilted the crucible and effected the formation of large globules. However, some granules were created, proving the Quimbaya's capability of reaching the correct temperatures to undertake granulation. Courtesy of Katharina Vones, 2023.

the ambient atmospheric temperature inside the chamber. This data would enable us to optimise the manufacturing process by reducing the length of time the silver was left in the furnace to the minimum needed to ensure spheration. After the firing cycle, the saggars were carefully placed in a chamber assembled of firebricks at ambient temperature to ensure cooling down without outside disturbance (Figure 12).

This rich, direct, and embodied experience of engaging with the charcoal-fired furnace, and in turn with fire as a material, needs to be contrasted with the almost total lack of physical connection the operator has when using a modern electric kiln. The process of energy input is achieved by flicking a switch. The variations in temperature are delivered by a pre-programmed digital controller and pyrometer setup. The operator never even needs to look at the sample during the firing and indeed is often unable to do so; most modern kilns lack a viewing port. Once it is known that the firing cycle works, it is only necessary to reset it and allow it to finish. The art and mystery of individual fire management that was acknowledged by Agricola and Ercker and practised up to the mid-twentieth century has now been reduced (and perhaps diminished?) to an electronically mediated, standardised, and highly abstracted operation. It also vastly limits the potential of the contemporary maker to perceive fire as a material whose direct manipulation can become an essential part of embodied making practices. As Brinck points out: "a certain kind of movement and manner of touching the material leads to the transformation of behaviour and the emergence of complementary patterns of practice. Attaching equal importance to sensing and acting on the felt results in the continuous improvement of skill and increased complexity."[54]

The experiments described in this article bear witness to the validity of this experiential approach for the contemporary maker with respect to the ancient technique of granulation and outline a methodological approach that includes both traditional and modern elements.

Considering the assay furnace as a specialised piece of equipment

Using the assay furnace to granulate silver was undertaken to examine the impact the reducing atmosphere of a charcoal-fired furnace would have on the process. However, moving from the abstract idea of testing the benefits of a reducing atmosphere to developing a viable programme of practical experiments to prove this, entailed numerous design decisions. As noted, the CNC cut graphite blocks enabled easily observable, accurate, and precise results. But it was necessary to work within the limitations of the furnace as already constructed: all the setters and saggars had to fit in a muffle chamber that had not been optimised for their low, wide dimensions. Cupellations are conducted using a cylindrical cupel with a diameter similar to its height; in addition, a clear space is needed above this to allow air to pass over the cupel and for the assayer to observe the reaction.[55] The issue of fit became even more pressing once the thin-walled vitrified saggars had to be replaced by thicker-walled stoneware ones.

That the most intractable problem centred around the one structural element of the furnace that could not easily be reconfigured was not coincidental. It indicated the extent to which the use of a modular assembly approach enabled multiple structural changes which could be easily undertaken without time-consuming and costly manufacturing implications. Similar modular systems are used elsewhere in scientific experimentation, for instance *Quickfit* glass, bringing similar benefits.[56] Though the difference between the shapes of the granulation setters and fire assay cupels meant the muffle's interior profile was not ideal, it was also not totally compromising. In contrast, the redox potential of the charcoal-fired furnace was more useful for granulation than for cupellation. When conducting cupellations in a solid-fuel furnace, the highly reducing atmosphere has to be mitigated by passing oxygenated air over the top of the cupel, whereas for granulations the reducing atmosphere was ideal for stopping oxygenation, eliminating the need for post-firing cleaning

[54] Ingar Brinck, "Craft Thinking," 37.

[55] See Oakley, "Fire Management in Practice" for a more detailed description of the process. Technical descriptions of the form of the cupel and a full account of the test observations needed can be found in Shepard and Deitrich, *Fire Assaying*, 46–62 and 56–64.

[56] or a description of how interlocking modular glassware was invented see Andrea Sella, "Friedrichs' Joints," an Opinion article in *Chemistry World* published online (6 January 2020) by the Royal Society of Chemistry https://www.chemistryworld.com/opinion/the-story-of-quickfit-part-one-friedrichs-joints/4010557.article (accessed 19/09/2025).

FIGURE 14 Granules of 6 mm inside the Graphite setter, straight out of the furnace. Note the bright, even surface of the granules. Courtesy of Katharina Vones, 2023.

(Figures 14 and 15).[57] The tests also demonstrated the capacity of assay furnaces designed for cupellation to reach temperatures beyond those needed for that activity. Whereas cupellations are conducted between 840°C and 950°C, to melt the silver inside the granulation setters required a temperature of 1025°C.

Although the individual setters became fixed entities once manufactured, their methods of manufacture (CNC milling), allowed for significant iterative and measurable changes to be made between the production of each setter and for easy replication of any existing setter. As the setters were replaceable, using them for potentially destructive experiments, such as testing in the open chamber, became less problematic. Undertaking these experiments led to a more profound understanding of the demands and limitations of the furnace assemblage and its operational needs, as well as adding to our knowledge of the range of possible approaches to conducting granulation in a charcoal-fired furnace.

The results show there is no “right” type of furnace for any specific operation, though there are definitely furnace designs that are borderline dysfunctional or completely unsuited to a particular task.[58] A charcoal-fired assay furnace designed for cupellation can be successfully repurposed to undertake granulation tests. This

[57] See Shepard and Deitrich, *Fire Assaying*, 46–73.

[58] Lawrence M. Principe, “Chymical Exotica in the Seventeenth Century, or, How to Make the Bologna Stone,” *Ambix* 63 (2016): 118–44.

FIGURE 15 3 mm granules inside the custom saggar made from crank clay. Note the bright, polished appearance of the granules and slight cracking of the saggar after repeated use. Courtesy of Katharina Vones, 2023.

is, in part, due to the similarity in these tests' sample size and the required temperature ranges. A suitable furnace can be optimised to undertake a particular process, but only in the sense of balancing the competing demands of that process. Factors to consider include the temperature range and type of atmosphere needed, the type of fuel, the construction materials, the form and role of any special elements, the overall structure and scale, the number of tests to be run, and the hours of operation. All these aspects have to be considered and their negative impacts ameliorated sufficiently. Though it is certainly possible to build versatile furnaces, the trade-off is a reduced capacity for undertaking very specialised tasks efficiently.[59]

At the same time every furnace has an optimum point of operation: each of the test furnaces tended to fire to a specific temperature range unique to its design. Operating outside of that range (either higher or lower) could only be achieved through constant diligence and repeated interventions. Making small changes to the design, such as changing the number and placing of the vents in the muffle, extending the length of the chimney, or altering the cross-section profile of the fire chamber, had a direct effect on this optimum temperature range.[60] Adjusting the venting arrangements through the muffle wall furthermore significantly changed the redox potential in the muffle chamber's atmosphere. So though one static, fixed furnace design

[59] Thijs Hagendijk, Márcia Vilarigues, and Sven Dupré, "Materials, Furnaces, and Texts: How to Write About Making Glass Colours in the Seventeenth Century," *Ambix* 67 (2020): 323–45.

[60] See Oakley, "Fire Management in Practice" for a more detailed discussion of structural changes.

cannot be considered a universal tool, treating the furnace as an assemblage with many mutable elements extends its capabilities and applications to a remarkable degree, though total flexibility is probably an unachievable ideal. Where universality actually lies is in the mind of the experienced furnace builder. Every new furnace build and alteration extends the builder's understanding of how each element contributes to the overall operation of the assemblage and each subsequent construction then benefits from that accumulated knowledge.

Conclusion: granulation as a technique through time

Undertaking a programme of granulation experiments in a charcoal-fired furnace presents an informative case study for fire management in practice and for the wider implication these experiments might have for the contemporary maker. It helped expose the longer-term consequences of the initial decisions made around the furnace design, the implications of changes in material selection and form of the refractory objects (setters, saggars), and the impact of structural intervention (e.g. adding vents to the muffle chamber). It enabled us to celebrate successes as well as to learn from failures. Using the methodologies described above, we were able to produce spherical granules up to a size of 6 mm (Figure 14) with beautifully smooth surface characteristics that needed little to no post-processing.[61] The smaller sizes up to 3 mm also displayed excellent, smooth surface characteristics that gave a bright, almost polished, appearance straight out of the furnace (Figure 15). This sets them apart from previous experiments conducted by Huycke in electric kilns, whose granules needed extensive polishing to gain uniformly smooth contours. This can mostly be attributed to the faster cooling cycle that is achieved using the method described above, as well as the exceptionally reducing atmosphere of the charcoal-fired furnace. These results are of great importance to the contemporary maker who wants to achieve a balance between producing granules of the highest quality in large volumes. While most contemporary makers will not have access to the type of furnace discussed here, future experiments will include tests in commonly available electric enamelling kilns to see if the combination of graphite setters and powdered charcoal in the clay saggars can produce a similar, locally reducing atmosphere without using charcoal as a fuel. Future steps will also include a closer analysis of the granules' surface characteristics, utilising electron microscopy and other archaeometallurgical methodologies, with a view to comparing granules from both sets of experiments with Tan, Yang, and Ji's findings.[62]

These experiments also raise questions around the nature of the methodological approaches used in contemporary craft practice. What does experimenting with

[61] Despite the slight deformations visible in some of the larger sizes (4 mm & 6 mm), this can mostly be attributed to an overfilling of the cells and will be easily rectified in future experiments by adjusting both the size of the cells as well as the amount of metal placed within them.

[62] Tan, Yang, and Ji, "Experimental Simulation of the Ancient Production of Gold Granules," 5–7.

historical techniques, used in conjunction with modern materials, tools, and digital making methodologies, contribute to our knowledge of what it means to be a maker, both in the present and in the past? In the case of granulation, this question becomes even more pertinent, as so little is known about how this technique was actually practised in ancient goldsmithing workshops, yet so much theoretical speculation endures. More experiments of the type presented in this article are required, with an emphasis on assembling teams of researchers that include makers as well as historians and scientists, to bring expertise from historical and contemporary practices into creative conversation. This will not only aid historical research by providing practical insights into the use of materials and tools in ancient techniques, but also allow contemporary makers to explore how current methodologies could be applied to those techniques. As Holt and Yamauchi comment, "craftwork tradition becomes a form of temporal binding in which the manufactured (and increasingly digitized) present is experienced as ephemeral (superficial, tasteless, flimsy, mass) and totalising (uniform), in contrast to the past, which was substantial and regionally distinct and various."[63]

Many of the debates around granulation as a technique revolve around the quest for authenticity, but in the absence of definitive, written source material, it is fruitful to explore how the past and present can interface to create novel methodological insights. The technique of granulation, which has persisted over thousands of years and fascinated scores of craft practitioners, provides contemporary makers with a link to the past and has been enthusiastically embraced in different settings. To break away from the temporal bindings of tradition and develop new pathways towards a future craft practice, conducting the types of experiments described in this article becomes essential.

The experiments presented here also provide an insight into what historical practice might feel like on an experiential level to contemporary makers, without laying claim to narratives of reconstruction or authenticity. Instead, they point to a pathway that constructs the past as existing in parallel with the present. Through these experiments, we envision a future craft practice in which the knowledge gained from such practice-led research can lead to new insights, both technical and historical. This can be framed by considering Martina Margetts's notion of the "materiality and processes of craft embody[ing] a narrative of lived experience."[64] Our lived experience as contemporary makers – conducting curiosity-driven experiments in a space filled with machines dedicated to digital ways of making – differs wildly from that of the Etruscan goldsmith or the early modern European chymist. Yet, the contemporary goldsmith still uses many ancient techniques and tools, perhaps made today from modern materials, but otherwise unchanged for centuries. But what can we learn from directly handling the types of equipment

[63] Robin Holt and Yutaka Yamauchi, "Ethics, Tradition and Temporality in Craft Work: The Case of Japanese Mingei," *Journal of Business Ethics* 188, no. 4 (2023): 827–43.

[64] Martina Margetts, "Taking Time: Craft and the Slow Revolution," *The Journal of Modern Craft* 3, no. 3 (2010): 373–75.

that have been radically changed by technology over time? Consider Elizabeth Grosz' question:

> How is it possible to revel and delight in the indeterminacy of the future without raising the kind of panic and defensive counterreactions that surround the attempts of the old to contain the new, to predict, anticipate, and incorporate the new within its already existing frameworks?[65]

While this project was not a typical reconstruction, it still makes wider contributions to an understanding of fire management across multiple historical periods. The notion that fire can be perceived as a material, to be manipulated, nurtured, and sculpted according to the maker's needs, is an insight useful both for understanding historical workshop practices as well as shaping novel modes of making in the present and future.

Disclosure statement

No potential conflict of interest was reported by the author(s).

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[65] Elizabeth Grosz, "Thinking the New: Of Futures Yet Unthought," in *Becomings: Explorations in Time, Memory, and Futures* (Cornell, NY: Cornell University Press, 1999).