The Ancient Craft of Granulation

A RE-ASSESSMENT OF ESTABLISHED CONCEPTS

Jochem Wolters
Seevetal, Federal Republic of Germany

Granulation has been used since ancient times to produce metal grains, usually of gold and its alloys, which have served in the fabrication of jewellery. The historical development of granulation and its technical characteristics are reviewed here, in advance of the publication by the author of a detailed book on these subjects.

Rarely has a single technique been the subject of such protracted, contradictory and sterile argument as the ancient craft of granulation. The futility of this discussion suggests that it was based on false premises. It is worthwhile, therefore, to examine the circumstances under which it arose.

Modern interest in granulation, dating from the period of Classicism, began in France in the late 18th century, spreading to Italy (Figures 1 and 2), the Netherlands, Germany and Russia (Figure 3). This interest continued through the 19th century, aided by the publicity surrounding finds of Greek and Etruscan jewellery, and reached a peak against the background of the revival of traditional arts and crafts in England and Germany between 1913 and 1936.

When 'modern' interest in this historical technique was first awakened during the period 1778 to 1850, goldsmiths and the emerging jewellery industry tried to imitate granulation work by casting and stamping processes (1). Moreover when more formal investigations into the ancient technique began after 1850, these were also conducted almost exclusively by goldsmiths (2). As was typical of the time, this research was characterized by an excessive interest in aesthetic aspects, by a one-sided emphasis on Greek and Etruscan work and by inadequate research into original literature sources. These attitudes, together with a tendency to overestimate the validity of practical experiments, led to acceptance of the following views concerning the process:

(1) Ancient granulation was an independent technique, unrelated to other jewellery techniques
(2) It was based on only one joining process
(3) Knowledge of the process had been lost
(4) No written record of granulation had survived
(5) The details of the ancient technique could be established by experimentation alone.

These concepts were subsequently taken over by art historians (3) and have dictated discussion to this day (4). It will be shown in what follows that they do not bear close scrutiny.

The Term 'Granulation'

Present day history of art defines granulation as a technique of decoration whereby the goldsmith arranges small grains of metal, or granules, in an ornamental or figurative pattern on a metal surface. The granules are held in place by joining them to the substrate. This simple, apparently self-evident definition from the latter half of the 19th century is misleading from two points of view.

First, granulation may be regarded as an independent branch of the goldsmith's art only on the basis of the aesthetic result. From a strictly technical point of view, however, it does not differ significantly from other methods of decoration of metal surfaces, such as filigree work, which also use joining processes (5). It is therefore understandable that ancient authors, basing their thinking on purely technical categorization, did not describe, or even see, granulation as an independent technique.

Secondly, it is unfortunate to describe the technique by a term which up to the beginning of the 19th century had an entirely different meaning. Thus, 'granulation' and 'to granulate' (from the Latin *granum* = grain) originally signified 'the production of grains of metal'. These were of value because they could be easily dispensed. Both terms, used in the original sense only, may be found in literary sources dating back to the 15th century (6). The modern usage of 'granulation' to describe the technique of decoration itself (7) has made the search for references to this technique in ancient sources a difficult task.

If, however, the ancient literature is analyzed without false expectations arising from the above and purely for its technical contents, it is soon found that descriptions of all the separate operations involved in granulation are embodied in a number of writings. It is therefore possible to reconstruct the ancient technique from a study of these sources.

Technical Characteristics of Granulation

In order to gain a full appreciation of the significance of literary sources as a means of throwing light on the ancient granulation technique it is necessary to examine the technical characteristics of antique granulation work.

Materials

Gold alloys are the most common materials of ancient granulation work, and the oldest examples are those found at Ur, dating from 2560 to 2500 B.C. (8).

Much of the early gold granulation work consists of silver-rich granules on copper-rich substrates. This is the case in finds from Alalach, in Syria (1750 to 1600 B.C.) (9) and those from the tomb of Tutankhamen (1352 B.C.) (10). However, in Etruscan work of the 7th century B.C. (Figures 4 and 5), analyses revealed that both the granules and the substrate are silver-rich with compositions in the ranges 65 to 67 gold/30 silver/3 to 5 copper (11) or 60 to 65 gold/30 silver/5 to 8 copper/2 others weight per cent (12).

Granulation in gold on a gilded silver substrate is reported for a 7th century fibula from Marsigliana (13), and on copper for a Trojan decorative pin dating from between 2350 and 2100 B.C. (14).

Granulation in silver alloys never achieved the delicacy of that in gold alloys and there are no reports of differing compositions for the granules and their substrates. The oldest known examples were found at Tell Brak, in Syria (2370 to 2200 B.C.) (15). Silver granulation artefacts of Greek (16), and central and northern European origins (17, 18, 19) are described in the literature and have been dated to periods extending from the 6th or 7th century B.C. to the 12th century A.D. More recently, silver granulation became common in the folk-jewellery of Germany from the 16th century onwards (20), of Bulgaria in the 18th century (21) and of Mongolia in the 19th century (22).

Gilded silver granulation is known from Urartu (23), in eastern Turkey, and silver granulation on silver-coated bronze substrates was used for the decoration of weapons of the 2nd century B.C. (24) and jewellery of the 11th century (25), which were found in Sweden.

Ancient granulation work in copper is very rare, one of the few examples known being a Spanish bridle decoration of the 15th century (26). Granulation in brass is of modern origin (27).

Granule Size

The grain diameter of the earliest granulations, those of the Royal Tombs of Ur (2560 to 2400 B.C.), is 2 mm (28), whereas that in work from Troy IIg (2350 to 2100 B.C.) ranges between 0.4 and 1.1 mm (29). The size of granules of the classical Greek period (510 to 330 B.C.) (30), and of the first two phases of the Etruscan culture (700 to 475 B.C.) (31), is of the order of 0.25 mm. The smallest granules, 0.14 mm in diameter (32), are to be found in Etruscan dust granulation (Figures 4 and 5) and the coarsest, measuring several millimetres in diameter, in Awarian work of the 9th century in Hungary (33). The fitting of granules of different sizes to the same item of jewellery was practised by several cultures, including the Etruscan (Figure 5).

Number of Granules

The number of granules used on a simple item can be of the order of thousands. Thus, a Greek necklace from Kameiros (7th century B.C.) bears 2 600 granules (34); a pendant from Enkomi, in Cyprus, (14th century B.C.) has 4 200 granules (35); and each of a pair of Etruscan bracelets from Tarquinia (7th century B.C.) is decorated with 20 000 granules (36). The largest known number of grains on a single item (137 000) is that on an Etruscan gold cup originating from Praeneste, and which has been dated to the 7th century B.C. (37).

Types of Granulation

The granules may be arranged in a variety of ways which goldsmiths use in different combinations depending upon the shape of the substrate (38).

Separate or point granulation, in which there is no bonding of one grain to another, is used mainly for the decoration of wires, though it is to be observed in round gallery arrangements on articles of the 7th century from Greece. It is found applied, for example, to Egyptian wire spirals dating back to 1910 B.C., to plain, corded and beaded wire eyes of the 2nd to the 11th centuries from various parts of Europe, and to wires in other types of designs from the same source and over the same period.

Linear granulation, in which the grains are arranged in lines, is very rarely applied directly to smooth surfaces. Usually the grains are set in grooves or flutes stamped or chased in the surface of the substrate. A rare exception to this is to be seen in Figure 4. The earliest examples of linear granulation originate from Troy and date back to 2350 B.C. Linear arrangements are also found in settings between wires of different types and upon double round wire. Examples of these (Figures 6 and 7) originate from various sources in the Middle East and Europe over a period extending between 2350 B.C. (Troy) and the 14th century (Russia). Free-standing linear arrangements in which the granules are attached to one another but not to a supporting surface are of four

Fig. 1 Gold pendant with point granulation and rosette-shaped massed granulation. The centre section is of glass mosaic. The height, including the link, is about 61 mm. Rome, around 1875. Schmuckmuseum, Pforzheim, inventory number KV 40

Photograph by Günter Meyer, Pforzheim

kinds: between round wires (China, 7th to 8th centuries); in annular form (Ur, 2560 B.C.); as unarticulated chains (Byzantium, 6th century) and as three- or four-row strips obtained by cutting up plates of granules, previously joined by soldering (Rome, 2nd to 3rd centuries B.C.).

Massed or field granulation, in which the grains are packed together in sheets and joined to the substrate, are found both without (Figure 8) and with surrounds which may be provided by embossed decorations (Figure 9)or by round, beaded or corded wires. Free-standing granulations in which there is no attachment of the granules to a substrate surface are known in the form of triangles from Ur, rhomboid shapes from Egypt, and as rosettes and five-pointed stars with wire borders, also from Egypt (Figure 7). Even the surfaces of wires may feature decoration by massed granulation.

Cluster or grape-like granulation, in which three-dimensional structures are built up by bonding together of granules, is known in many forms. The granules may be bonded to a backing substrate sheet,

Fig. 2 Gold earring with point, linear and rhombic massed granulation. This reproduction of a Greek earring kept in Leningrad was made by Giacinto Melillo in Naples around 1888. The height of the piece is 55 mm. Schmuckmuseum, Pforzheim, inventory number KV 269

Photograph by Günter Meyer, Pforzheim

Fig. 3 Gold bracelet with linear granulation, enamel and precious stones. This piece is probably of Russian origin (mid-19th century) and was allegedly the property of Alexandra, the wife of the last Czar. The overall length is 190 mm and the width 75 mm. Schmuckmuseum, Pforzheim, inventory number 1967/20

Photograph by Günter Meyer, Pforzheim

as in Danish work of 300 A.D., bonded to the outer edge of jewellery items as in Ostrogothic work of 400 A.D. (Figure 6), designed as stiff pendants as in examples from Iran and Germany, fitted to corded wire rings as in certain Russian items (1568 A.D.), or attached as tops or crowns on small cylinders as found in German work of 962 A.D.

Remnants of Joining

All surviving historical granulation work may, by visual inspection, be allocated to one or other of two groups (39).

Granulations with clearly recognizable traces of solder alloys originate from Egypt of the Middle Kingdom era (1910 B.C.) (Figure 7), from Iran since the end of the Parthian period (1st to 2nd centuries A.D.), from pre-historic northern and central Europe (6th century B.C. to 4th century A.D.), from Imperial Rome (2nd to 3rd centuries A.D.), from Byzantium (3rd to 11th centuries A.D.), from northern Europe of the Migration Period (4th to 7th centuries A.D.) as well as from central and southern Europe from medieval times onwards.

The granulation work of virtually all other cultures, on the other hand, shows no remnant of solder alloys whatever. This holds true particularly for Mesopotamia since the period of the earliest dynasties (2500 B.C.) (Figure 10), for Syria from 2370 B.C. onwards, for Troy IIg (2350 to 2100 B.C.), Transcaucasia from 2128 B.C., Egypt since the Middle Kingdom (1800 B.C.), Crete subsequent to the Middle Minoan Stage IB (1800 B.C.), Palestine since the middle of the Bronze Age (1625 B.C.), Iran after the 16th century B.C., Greece since early Mycenaean

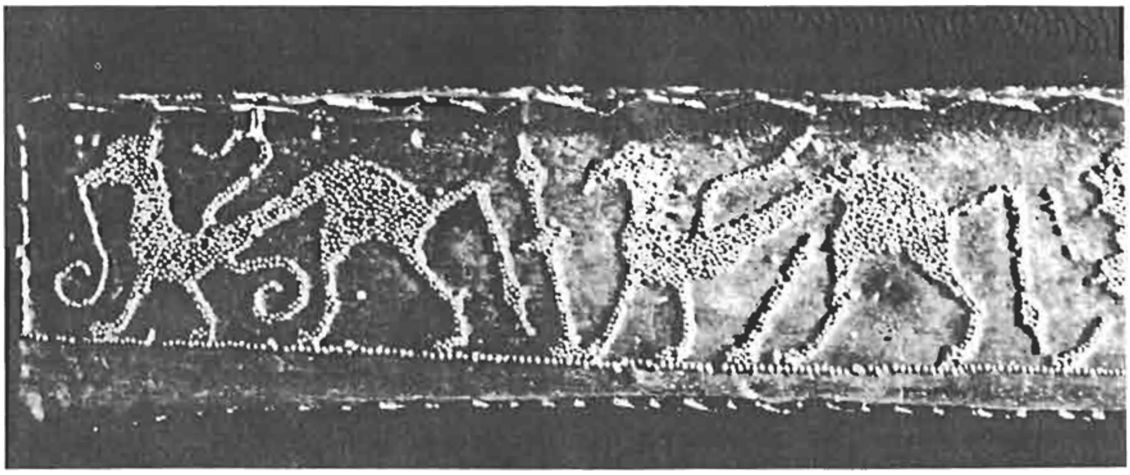


Fig. 4 Etruscan gold fibula with dust granulation in silhouette style. This piece was found at Vetulonia and dates from the mid-7th century B.C. The length of the detail shown here is 50 mm

Photograph by Museo Archeologico Nazionale, Florence

Fig. 5 Etruscan gold disc earring with dust and linear granulation, from Piombino, Populonia (6th century B.C.). The piece is 45 mm in diameter. Schmuckmuseum, Pforzheim, inventory number 1969/116

Photograph by Günter Meyer, Pforzheim

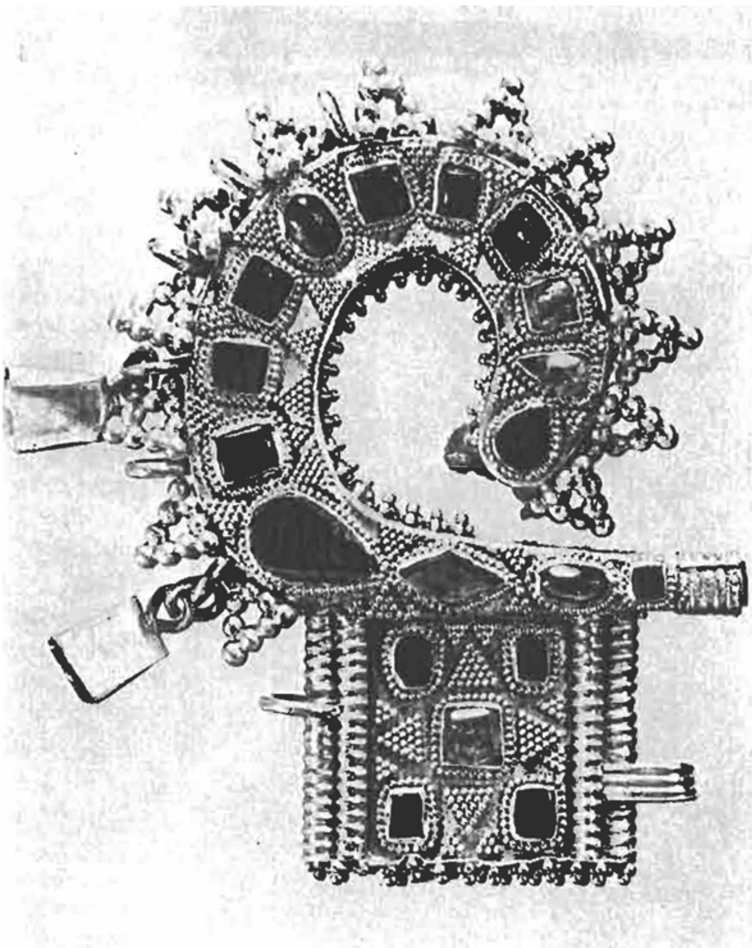


Fig. 6 Ostrogothic gold work (earring?) with linear, field and cluster granulation, precious stones and glass, from Varna, in Bulgaria (around 400 A.D.) The height is 73 mm and the width 52 mm. Römisch-Germanisches-Museum, Cologne, inventory number D 291a

Photography by Rheinisches Bildarchiv, Cologne

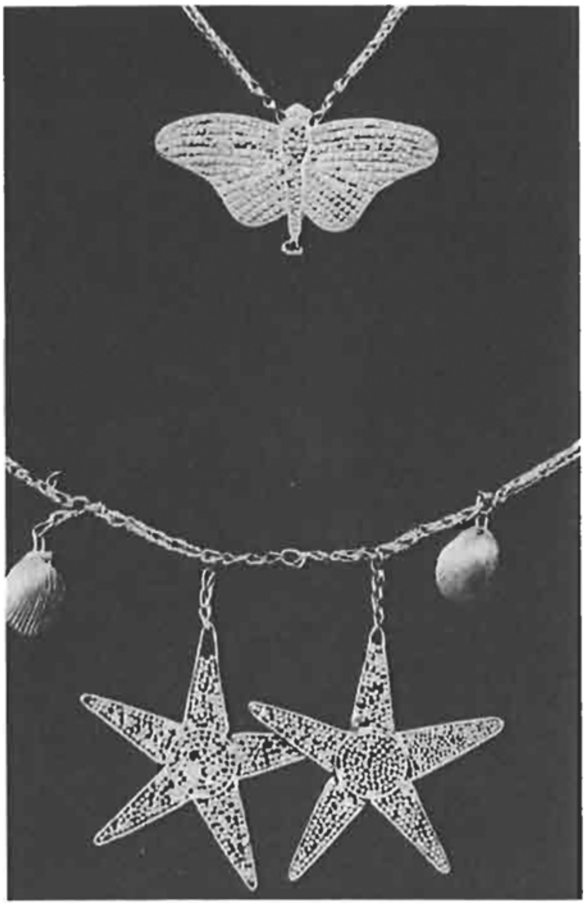


Fig. 7 Details of Princess Chemenet's necklace with linear and massed granulation, found at Dahchour, in Egypt (around 1910 B.C.). The stars are 25 mm across

Photograph by the Cairo Museum

times (1600 B.C.), Cyprus after 1550 B.C. and for Etruscan work since the First Phase (700 B.C.) (Figures 4 and 5).

It can be said that none of the numerous attempts at experimental reconstruction of the historical granulation technique (40) has taken adequate account of the above important considerations.

The Technique of Granulation

After preparation of the substrate, the process of granulation comprises three obvious steps: the production of granules, adhesive fastening of these to the substrate — gravity positioning being unsuitable on most shapes other than flat — and joining the granules to the substrate.

Many accounts of all these processes are found in the historical literature and some of these are examined below, viewed against the technical features of ancient granulation work.

Production of Granules

The fact that small metallic particles tend to assume a spherical shape on melting is familiar to all those involved in metalworking. It was therefore not the formation of grains of spherical shape which posed a problem in antiquity, but rather the satisfactory and economic production of such grains in large numbers. Most historical accounts have, therefore, been written against this background.

Various methods (41) of manufacturing granules for the convenient dispensing of metals and alloys have been described by Pliny in 79 A.D. (42), V. Biringuccio in 1540 (43), G. Agricola in 1556 (44), B. Cellini in 1568 (45), M. Fachs in 1595 (46) and A. Libavius in 1597/1606 (47). However, only those of the above which are based on the melting of small metal particles yield perfectly spherical grains. Of the latter processes, that described by Biringuccio, in which

Fig. 8 Gold ear pendant, with field and cluster granulation in pyramidal shapes, of Caucasian origin (4th to 7th centuries A.D.). The length is 110 mm. Schmuckmuseum, Pforzheim, inventory number 1957/4

Photography by Günter Meyer, Pforzheim

flattened wire cuttings are stacked alternately with layers of charcoal in a crucible and heated above the alloy melting range, would appear to yield the most uniformly sized spherical grains.

Prior to the invention of the draw-plate in the early Middle Ages (7th century A.D.) (48) fine wire was manufactured by rolling strips of sheet metal (49) and it seems likely that in view of the extra cost and labour of the rolling stage, granules produced before the 7th century A.D. would have been manufactured by melting pieces of cut-up metal sheet of strip. The invention of the file in the 7th century B.C. (50) would have made possible the production of extremely fine particles and indeed it is from this period that the Etruscan dust granulations (Figures 4 and 5) were produced. The coarse grain structure expected in granules manufactured by the melting of small metal particles may be clearly seen on a microsection of a fragment of an Etruscan fibula dating from the 7th century B.C. (51).

Positioning of the Granules

The attachment by means of organic adhesives of small metal parts onto receptors was described by Theophilus in 1122/1123 (52) and by Cellini in 1568 (53), the former dealing with the fastening of beaded wire ornaments by flour paste. Since no other adhesive for this purpose is mentioned by him it must be assumed that flour paste was also used in granulation work at the time. Cellini describes the sticking of granules onto wire substrates by means of tragacanth (gum).

Apart from flour paste and tragacanth, four further adhesives for the positioning of metal parts onto substrates are described in the ancient literature. Glue made from cattle hides and termed 'ox-glue' is mentioned in a 6th or 7th century Syrian adaption of Zosimos (54) as a component of an adhesive solder, and soap, a product first developed by the Gauls (55), is cited as part of a similar mixture in the *'Compositiones'* of the 8th century (56) and by Theophilus (57). Quince paste (glue) and gum arabic, the latter already known to the Egyptians (58), receive mention by Biringuccio in 1540 (59). Fish glue, already known in pre-classical times (60) is described by Theophilus (61), but not termed an adhesive. Since, however, it is among the oldest glues known to man, its use in granulation work of ancient and classical times may be assumed.

The Joining Process

The attitudes which prevailed at the beginning of the historical investigation into granulation, and particularly the great attention given to Etruscan and Greek examples of the craft (which indeed display no sign of solder alloys), led to the erroneous idea that genuine granulation is produced without the use of solders. Accordingly, granulation work with recognizable remnants of solder is to this day inappropriately referred to as 'pseudo-granulation'.

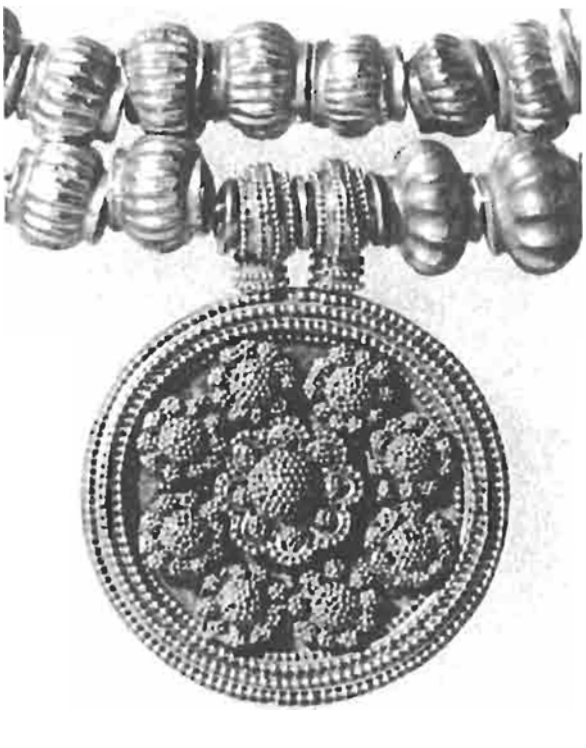
This extrapolation of the characteristics of the products of a single epoch to the entire history of the craft ignores the fact that numerous cultures throughout the four-and-a-half thousand year history of granulation worked exclusively with metallic solders. The examples cited earlier in this article, in fact show this to have been the case for more than half of this period.

While the numerous examples of granulation showing clearly recognizable remnants of solder were obviously produced using solder alloys and fluxes known in ancient times (and there is no evidence that these were in any way different from those used for other goldwork), granulation without trace of solder must have been produced using another process. The numerous attempts to identify this process have caused much confusion. However, careful study of the literature reveals that a joining process which uses adhesive non-metallic solders and which would produce the technical characteristics of solderless granulation bonding, was known continuously throughout two millenia.

Among modern techniques used in attempts to reproduce the ancient joining process in granulation (62) are welding by the 'melting interval' (63) and 'alloy' (64) methods. However, the high degree of temperature control required by these methods is incompatible with the crude limitations of the charcoal fire. Furthermore, in the case of the 'alloy' method, common melting point depressants such as phosphorus, silicon or bismuth were unknown in ancient times (65). Other reasons to conclude that neither welding technique is likely to have been used for historical granulation are that they are not mentioned in the source literature and that they are not applicable to the impure alloys used in antiquity. Moreover, the 'melting interval' and 'alloy' methods are not suitable for bonding granules to wire or intricately shaped substrates because of the non-uniformity of temperature distribution when receptors of these types are heated.

Sintering has also been used in attempts to reconstruct ancient granulation bonding, exploiting the increased energy density on the surface of small spherical bodies, together with the high self-diffusion of gold. However, the process is basically applicable to high carat gold alloy formulations for which there is no evidence of use in antiquity (66), and would appear to be incompatible with the historical gold alloys of high silver or copper content. A further factor mitigating against its use in ancient granulation would have been the difficulty of achieving even

Fig. 9 Detail of a Greek gold bottle-stand with irregular field granulation of the reserved silhouette style (around 500 B.C.). The diameter of the piece is 150 mm Photograph by Musée du Louvre, Paris



heating with fully deformed, hollow or wire substrates, granules and substrates of different compositions, or when bonding wires and granules to the same piece.

The very ancient technique of joining with non-metallic (colloid) solders (67) relies upon the reaction of copper compounds, applied to the areas to be joined in admixture with organic adhesives (which also act as reducing agents), to form copper(II) oxide CuO, the reaction taking place at 100°C. Carbonization of the adhesive (600°C) causes reduction of the oxide to metallic copper (850°C), which in turn forms a eutectic with silver and a near-eutectic with gold alloys of high silver content. The same reaction with gold alloys of high copper content occurs at about 900°C. Bonding is thus achieved by surface alloying.

Fig. 10 Detail of a gold necklace from Dilbat, in Mesopotamia (17th century B.C.). The pendant, 25 mm in diameter, is decorated with linear and rosette-shaped granulation

Photograph by The Metropolitan Museum of Art, New York

Prolonged and repeated heating leads to increased diffusion depths and ultimately to uniform distribution of the copper in the gold, leaving no surface residue. Modern analytical confirmation of joining by means of non-metallic solders would therefore have been possible only on ancient samples for which the heating times had been short.

The use of ten copper compounds as non-metallic solders has been traced in the literature. The oldest of these is malachite, from the Egyptian 'mafek', a mineral form of the basic copper carbonate $CuCO_3.Cu(OH)_2$. Malachite, or its Greek derivative 'chrysokolla' (literally 'gold glue' or 'gold solder'), is referred to frequently from ancient times through to the 16th century (68 to 89). Its first mention as a solder is by Theophrastus in 300 B.C. (73). The term chrysokolla changed its meaning in time and Agricola in the 16th century makes a clear distinction between the 'chrysokolla of the Ancients' and the 'chrysokolla which is called borax' (89). In the 19th century, Von Beudant first used the term to signify hydrated copper silicate (90).

Another basic copper carbonate of mineral origin, azurite $2CuCO_3.Cu(OH)_2$, has also been frequently described as a non-metallic solder in historical literature originating with Theophrastus (91).

Burnt copper, black copper(II) oxide CuO contaminated with red copper(I) oxide Cu_2O, is produced by the heating of copper sheet in air, and the first reference to its use in a solder is found in the *'Compositiones'* (95). It is mentioned in the literature as far back as the 17th century B.C. (92, 93, 94).

Two other copper oxide mixtures probably used in solder compositions, though this is not specifically mentioned in the literature, are copper scale, formed from the forging of copper, and copper bloom from the quenching of molten copper. Both substances consist of red Cu_2O contaminated with black CuO. This assumption is justified by the frequent confusion made in ancient times between the oxides of copper, which are quite frequently produced as mixtures (96, 97).

Verdigris, mainly copper(II) acetate pentahydrate $Cu(CH_3CO_2)_2.5H_2O$, was known to the Egyptians (98). Its production by the action of wine dregs on copper and its use as a substitute for the expensive chrysokolla were first described by Theophrastus (99). Later accounts give similar methods of production (100 to 103). The use of verdigris in goldwork has been reported by several authors, including Strabo in 30 A.D. (104) and Pliny (105).

The latest mention of verdigris being used in a solder was by Cellini in 1568 (106). Some of the literature on 'verdigris' appears to indicate that, in fact, patina, a basic copper carbonate of varying composition, was obtained, which functioned as a solder.

The preparation of the vitriol, cupric sulphate pentahydrate $CuSO_4.5H_2O$, was first reported by Dioskurides in 77 A.D. (107), and its use as a solder is recommended in the *'Compositiones'* (108). Later accounts, by Mizaldus in 1574 (109) and Libavius in 1597 (110), make mention of it in admixture with cupric oxide.

Theophilus reported a very complicated mixture based on cupric hydroxide $Cu(OH)_2$ for use as a solder (111). To prepare it, a mixture of copper oxides, cupric chloride and cupric hydroxide made by heating salt-coated copper plates was added to a composition made up from potash, soap and lard (producing the reducing carbon).

The above evidence suggests that the only proven technique for producing granulation which does not show any trace of solder alloy is that which uses adhesive compositions containing copper compounds such as those discussed. These were explicitly referred to in the literature as gold solders. Apart from the use of metallic solders, this is the sole technique for joining the granules to the substrate which could have been used with the only ancient heating facility — the open charcoal fire (112). Furthermore, bonding with non-metallic solders produces all the technical characteristics found in ancient granulation. Significantly, the method is applicable to all known combinations of metals and alloys used in ancient granulation, to substrates of all shapes and dimensions, and to wires and granules vastly different in size. The process may also be repeated without affecting existing bonds.

The following evidence should also be considered as support for the use of non-metallic solders in granulation: work from different periods frequently exhibits copper-coloured spots at the granule-substrate joints (113), and etching and subsequent analysis show the presence of copper at the contact surface (114).

Furthermore the term 'Santerna', used by Pliny for adhesive solder compositions is of proven Etruscan origin (115). Because, according to the same author, joining with adhesive non-metallic solder compositions is especially suited for gold alloys with high silver contents, which were the preferred materials of the Etruscans for granulation, it can be assumed that both the term and the technique go back to that era.

Continuity in the History of Granulation

Never since it was first used has granulation been a lost art. Until far into the 19th century, the time of its alleged 'rediscovery', this technique has thrived continuously in many places, for instance in Russia (116), Bulgaria (117), Mongolia (118), Tibet (119) and Persia (120). This also holds true for Swiss (121) and German (122) folk-jewellery. In this context, a reappraisal appears warranted of European granulation work stemming from the time of the 'rediscovery' (Figures 1, 2, 3). Because of the use of metallic solder in its manufacture this jewellery has been belittled as 'pseudo-granulation'. However, there is no technological difference between it and most of the granulation since the 1st century A.D., and the artistic qualities of the work are often of a very high standard.

Conclusion

It has been attempted in this study to show conclusively that debate on the ancient technique of granulation, hitherto clouded in confusion, has actually been based on five wrong assumptions, listed at the beginning of this article. From the above discussion the following conclusions may be drawn:

(1) Granulation is a formal discipline within the art of the goldsmith; however, it is not a technique which is based on one specific joining process

(2) In granulation, as in other jewellery techniques, both metallic and non-metallic solders have been used, the latter predominantly in antiquity

(3) Granulation was never a 'lost' art; it survived with continuity until far into the 19th century

(4) The descriptions of, or references to, joining techniques on which granulation is based can be found in numerous literary sources over a period of more than 2 000 years

(5) Modern attempts to establish by experiment the origins and characteristics of the technique have contributed little to our knowledge of it. They have usually ignored the technical features of ancient work and have not been based on the exclusive use of tools, materials and processes known in antiquity.

References and Notes

Owing to space limitations, this Section is restricted to important references. Extensive notes and references pertaining to the dates of sources, the secondary literature and the most significant examples of ancient granulation work can be found in two contributions by the author to 'Historische Technologie der Edelmetalle in Ludwigsburg', Udo Pfriemer Verlag, München, 1980, which are entitled 'Literary Sources on Granulation' and 'Technical Conditions for the Historical Development of Precious Metal Soldering up to the Late 18th Century (Blowpipes, Fluxes, Solders)'.

The history of granulation is discussed in a broader context in: J. Wolters, 'Zur Geschichte der Löttechnik', Degussa, Hanau-Wolfgang, 1975.

A monograph on the history, technique and 're-discovery' of granulation is also in preparation by the author for publication later this year by Callwey-Verlag, München.

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15 See (9), pp. 19, 27, 30 and 134
16 For example, Syracuse (tomb 404) and Megara Hyblea (tomb 240); see K. Hadaczek, 'Der Ohrschmuck der Griechen und Etrusker', Wien, 1903, p. 16
17 For example, sword-hilt from Brostorp/Öland, Sweden, (Stockholm Museum); see 'Sveagold und Wikingerschmuck', Mainz, 1968, fig. 21
18 For example, fibula from Tersev; see T. Capelle, 'Der Metallschmuck von Haithabu', Neumünster, 1968, p. 80, pl. 27
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20 For example, silver brooch from Bavaria; see (3), p. 3, fig. 4
21 For example, silver box from 1767; see (3), p. 3, fig. 2
22 'Jewellery through 7 000 Years', The Trustees of the British Museum, London, 1976, p. 197, fig. 323
23 For example, gilded silver earring; see (9), p. 199
24 For example, silver-plated spur from Hörninge/Öland (Stockholm Museum); see (17), fig. 52
25 For example, ring fibula from Tingstäde/Gotland; see A. Oldeberg, 'Metallteknik under Vikingatig och Medeltid', Stockholm, 1966, fig. 636
26 See (3), p. 3, fig. 6
27 *Gold und Silber*, 1968, (9), 108
28 C. L. Wooley, 'The Royal Cemetary', Vol. 2, London, 1934, p. 297
29 R. A. Higgins, 'Greek and Roman Jewellery', London, 1961, p. 19; see also (4), p. 34
30 C. Singer *et al.*, 'A History of Technology', vol. 1, Oxford, 1954, pp. 657 ff.; see also (29), pp. 19 and 36
31 See (30)
32 See (30)
33 G. Laszlo, 'Steppenvölker und Germanen', Herrsching, 1974, pl. 135 and 140
34 See (22), fig. 92 and 93
35 See (22), p. 53, fig. 40
36 See (29), pl. 35
37 D. E. Strong, 'Greek and Roman Silver Plate', London, 1966, pl. 27
38 Refer to the publications listed in the note introducing this Section.
39 See (38)
40 See (2); (4); W. T. Blackband, *Illus. London News*, 1934, (24 April), 659; H. A. P. Littledale, 'A New Process for Hard Soldering', London, 1936; G. Picardi, *Studi Etruschi*, 1952/3, **22**, 199-202 and F. Chlebecek, *Studi Etruschi*, 1952/3, **22**, 203-205
41 Most of these methods consist of dispersing a continuous flow of molten metal by means of a sieve, a mesh or twigs.
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43 V. Biringuccio, 'Della Pirotechnia', Venice, 1540
44 G. Agricola, 'De Re Metallica', Basel, 1556, Books VII and X
45 B. Cellini, 'Due Trattati: Uno Nitorno alle Otto Principali Arti dell' Oreficeria...', Florence, 1568, chapter 2
46 M. Fachs, 'Probierbüchlein', Leipzig, 1595, pp. 68-71
47 'Die Alchemie des Andreas Libavius', Gmelin Institut, Weinheim, 1964, p. 95
48 A. Kratz, *Aachener Kunstbl.*, 1972, **43**, 188, note 14; see also W. A. Oddy, *Gold Bull.*, 1977, **10**, (3), 79
49 See Kratz (48), 158-163
50 Forrer, 'Reallexikon der prähistorischen Altertümer', 1907, p. 208
51 See (12), pp. 355 ff.

52 Theophilus, 'Schedula Diversarum Artum', Book III, chapter 52
53 See (45)
54 M. Berthelot, 'La Chimie au Moyen Age', vol. 2, Paris, 1893, p. 258
55 See (42), Book XXVIII, chapter 12
56 'Compositiones ad Tigenda Musiva', edited by H. Hedfors, Uppsala, 1932, p. 175
57 See (52), Book III, chapter 51
58 F. M. Feldhaus, 'Die Technik der Vorzeit...', München, 1965, column 487
59 See (43), German translation by Johannsen, Braunschweig, 1935, p. 435
60 See (58), column 616
61 See (52), Book I, chapter 18
62 See (40)
63 See Chlebecek (40); E. Frey, *Dtsch. Goldschmiedez.*, 1956, (10), 476 and Anon., *Dtsch. Goldschmiedez.*, 1951, (6), 139-140
64 B. H. Rogge, *Dtsch. Goldschmiedez.*, 1951, (8), 207 (technical notes) and J. Schneider, *Dtsch. Goldschmiedez.*, 1951, (12), 318-319
65 See (58), columns 623, 796 and 1334
66 See Frey (63) and E. Treskow, in 'Diebeners Goldschmiede-jahrbuch', Stuttgart, 1959, p. 32
67 First described by Littledale (40), p. 47. The diffusion temperature of copper in silver given by this author is, however, wrong.
68 R. J. Forbes, in 'Studies in Ancient Technology', vol. 7, Leiden, 1955-1964, p. 106
69 'The Surgical Papyrus Edwin Smith', edited by Breatstedt, vol. 2, Chicago, 1930, p. 3
70 Gilgamesh Epic, table VII, part IV, line 6
71 C. R. Lepsius, 'Les Métaux dans les Inscriptions Egyptiennes', Paris, 1877, pp. 35-45 and 61 ff.
72 Hippocrates, 'De Fistulis', chapter VII
73 Theophrastus, 'De Lapidibus', paragraphs 26, 39 and 51 (including azurite)
74 Poseidon of Apamea, 'De Mirabilibus Auscultationibus', which has been erroneously attributed to Aristotle; see J. R. Partington, 'A History of Chemistry', vol. 1, London, 1961, pp. 75 ff. and 99 ff.
75 Strabo, 'Geographia'; see H. Kopp, 'Geschichte der Chemie', vol. 4, Leipzig, 1843-1846, p. 167
76 Vitruvius, 'De Architectura', Book VII
77 See (42), Book XXX, chapter 29; Book XXXIII, chapters 26 to 30; Book XXXIV, chapters 26 and 28; Book XXXVII, chapter 54
78 'Papyrus Graecus Holmiensis', edited by O. Lagercrantz, Uppsala-Leipzig, 1913, pp. 176 ff. and 194
79 'Papyrus Graecus Leidensis', chapters 28, 31 and 80; see M. Berthelot, 'Archéologie et Histoire des Sciences', Paris, 1906, pp. 281 and 297
80 'Codex Marcianus 299'; see M. Berthelot, 'Introduction à l' Etude de la Chimie des Anciens et du Moyen Age', Paris, 1889, pp. 104 ff.; see also (56), p. 192
81 'Codex Parisiensis 2327'; see Berthelot (80), pp. 112 ff. and (56), p. 192
82 Democritus, 'Physica et Mystica'; see M. Berthelot, 'Collection des Anciens Alchimistes Grecs', vol. 2, Paris, 1887/8, London, 1963, p. 69
83 Olympiodor, 575 A.D.; see Berthelot (82), p. 79
84 Zosimos, 9th century; see Berthelot (82), pp. 236 and 258
85 'Al-Razis Buch 'Geheimnis der Geheimnisse'', edited by J. Ruska, Berlin, 1937, p. 86, paragraphs 13 and 21
86 'Turba Philosophorum', edited by J. Ruska, Berlin, 1931, pp. 189, 204, 216, 219 and 238
87 Bar Balhul, 10th century; see (54), vol. 2, p. 130
88 V. de Beauvais, 'Speculum Majus'; see (54), vol. 1, p. 289
89 See (44)
90 C. Hintze, 'Handbuch der Mineralogie', vol. 2, Leipzig, 1897, pp. 460 ff.
91 See (73)
92 Tell-Umar texts, 17th century B.C.; see C. J. Gadd and R. Campbell Thompson, *Iraq*, 1936, **3**, 87-96
93 Chemical texts of the Assurbanipal period, 668 to 626 B.C.; see (68), vol. 5, p. 136
94 Dioscurides, 'Materia Medica', Book V, chapter 87
95 See (56), p. 175
96 See (43), Book XXXIV, chapters 107 ff.
97 See (94), Book V, chapters 87 to 89
98 A. Neuburger, 'Die Technik des Altertums', Leipzig, 1977, p. 120
99 See (73), paragraphs 56, 57 and 60
100 See (76), Book VII
101 See (94), Book II, chapter 99; Book V, chapters 91, 92 and 104
102 See (42), Book XXXIII, chapter 29; Book XXXIV, chapters 26 and 28
103 'Das Steinbuch des (Pseudo-)Aristoteles', edited by J. Ruska, Heidelberg, 1912, pp. 138, 178 and 192
104 See (75)
105 The diffusivity of copper in gold-silver alloys is higher than in pure gold or in copper-rich gold alloys.
106 See (45), chapter XXII
107 See (94), chapters 99 to 102
108 See (56)
109 A. Mizaldus, 'Memorabilium Sive Arcanorum Omnis Generis per Aphorismos Digestorum Centuriae IX', Köln, 1574, folio 125v
110 See (47), p. 177
111 See (52), Book III, chapters 57 ff.
112 See the author's contribution entitled 'Technical Conditions...' mentioned in the introductory notes to this Section.
113 J. Lang, in 'Proc. Symp. Aspects Early Metall.', edited by W. A. Oddy, London, 1977, p. 172; see also E. Treskow, *Dtsch. Goldschmiedez.*, 1953, (9), 265, and Kratz (48), 166, fig. 23 to 25
114 See (12) and Lang (113)
115 A. Ernout, *Bull. Soc. Linguis.*, 1929, **30**, 95
116 For example, gold goblet with diamonds (late 18th century); see W. Markowa, 'Der Kreml', Leipzig, 1975, pl. 102
117 See (21)
118 See (22)
119 For example, decorative sheet (late 18th century); see (22), fig. 319
120 For example, gold earrings (19th century); see 'Katalog: Schmuck aus Persien', Schmuckmuseum Pforzheim, 1974, Nos. 135, 144, 146 and 148
121 For example, gold-plated silver pendant (around 1800); see G. Ritz, 'Alter bäuerlicker Schmuck', München, 1978, fig. 239 and 254
122 For example, gold-plated silver shirt pin from Alten Land/Hamburg; see 'Abteilungs Katalog 2, Historisches Museum am Hohe Ufer', Hannover, 1972, pl. 35

SO gold, which is the most fixed of all bodies, seems to consist of compound particles, not all of which, on account of their massiveness, can be carried up by the agitation of heat, and whose component parts cohere with one another too strongly to be separated by that agitation alone.

From the translation by
A. Rupert Hall and Marie Boas Hall
Cambridge, 1962

ISAAC NEWTON
From the unpublished
Conclusio to the *Principia*
Cambridge, 1687