Decorative and Structural Granulation in Larger Silver Artefacts

David Huycke
Artist and Professor
PXL-MAD School of Arts, Hasselt & Hasselt University
Hasselt, Belgium

Granulation—Introduction

Granulation is an ornamental technique in jewelry art in which tiny metal balls, also called "granules," are heat-fused to a metal surface and to each other without the use of solder, generally in an ornamental or figurative arrangement. It is considered to be one of the most magical techniques in the history of goldsmithing. The technique originated in the third millennium B.C. in the Middle East and reached its technical and artistic peak in Etruria and Greece between the seventh and fourth century B.C. Exquisite pieces of mostly golden jewelry and small utensils, sometimes decorated with more than 100,000 individual granules, are witnesses of these great artistic and technical achievements.[1]

Granulation can be explained from an artistic and a technical point of view, since in goldsmiths' art the term "granulation" is generally used for two different ideas. The first approach places the intention of the goldsmith in the center, namely achieving an interesting visual effect which is accomplished by arranging lots of small granules in a certain composition on a piece of jewelry. This approach provides the identity of granulation, which is the sphere as an individual entity or as a part of a larger composition. The second, technical approach of granulation does not focus on the plastic or visual intention of the craftsman but on the joining process, on how the granules are attached to each other and to the supporting surface. Unlike traditional soldering where the metallic connection between the different elements is usually achieved by adding solder with a lower melting point, the connection in granulation is made through what is called "reaction soldering." Instead of solder, copper is applied as a binding agent, using the principle that copper is the diffusion agent and lowers the melting point in an alloy with silver or gold. Reaction soldering is a way of soldering that was used frequently in antiquity, and not just for granulation. It is a method that offers the possibility to create metallic connections so delicate and pure and which are hardly possible with traditional soldering.[2]

From the moment of its conception between 4,000 and 5,000 years ago to the present day, granulation has been mainly used in gold and on small objects, most often on jewelry and almost entirely for decorative purposes. These considerations are the starting points of the research presented here. This paper introduces examples where 1) fine granulation is applied on larger silver hollowware, and where 2) granulation is used as a building method for larger silver objects. As a general introduction to the technique, the different steps in the traditional granulation process are described: making the granules, arranging them on the surface and, finally, the reaction soldering process where granules and surface are connected.

Technical Process: Production of Granules

The production of the granules is a natural process, a consequence of a number of metallurgical, physical and thermal principles, which every goldsmith undoubtedly discovers during his or her practice. When a small piece of metal is heated to the melting point, the liquid metal will take on the smallest possible shape, a perfect sphere, due to its cohesive force and surface tension. When the molten mass cools down, it will solidify into the same shape. Thus, the granule spontaneously forms itself from any small piece of metal that is heated to the melting point, making it therefore much easier and faster to make identical granules instead of identical units of any other shape.[3] Because of this, the use of the sphere in granulation was most probably not based on a visual or artistic consideration but was dictated by artisanal and metallurgical processes and can be explained more technically than from an aesthetic or philosophical point of view.

The most common way to produce a large number of granules is to put small pieces of metal in a refractory crucible filled with charcoal powder and without the pieces touching each other. The crucible is closed and heated in a kiln to a temperature of approximately 100°C (180°F) above the melting point of the elements inside. The metal bits melt and, as described above, take the shape of little spheres.[4] The melting of the metal pieces works best in charcoal powder for two reasons. First, the charcoal powder makes the melted pieces of metal “float,” resulting in perfect globes. If the pieces are too big and consequently too heavy, they will sink through the powder to the bottom of the crucible, forming granules with a flat surface. Second, the burning charcoal ensures a reducing environment inside the closed crucible, and the liquid granules in the powder can’t absorb any oxygen, which is necessary, especially for silver granulation. Silver granules produced in open air absorb oxygen while they are in a molten state. During reaction soldering the oxygen escapes in the form of splashing when the surface of the silver is brought into a liquid state.[5]

After the crucible is heated up to the desired temperature and cooled down again, it is removed from the kiln. The content of the crucible (the charcoal powder and the newly formed granules) is poured out. When the granules are washed and sorted according to size, they can be positioned on the surface of the jewelry.

Arranging the Granules

Since thousands of granules are usually involved, which have a constant tendency to roll away, the small balls are first glued to the jewelry with a mixture of water, organic glue and a copper salt in powder form.[2] Getting the balls well glued to the substrate in the desired composition before the actual reaction soldering takes place is critical to success. The copper salt in the mixture becomes essential in the next phase of the granulation process, the metallic bonding. Because the glue mixed with the granules is a liquid substance, the granules tend to cluster together, making triangles, rosettes or double rows. These shapes are much easier to make than, for example, a straight line with a single row of granules.[6]

Reaction Soldering

When the granules are arranged in the desired composition, the next and final step in the granulation process is the actual metallic joining of the granules to the substrate and to each other. The object with the glued granules is gradually heated in a kiln, with a flame or with a combination of both. At 100°C/212°F, the copper salt converts into copper oxide. The glue, which holds the granules in place, carbonizes at 600°C/1112°F and creates a reducing area around the object, allowing the copper oxide to convert into metallic copper. This way, a very thin layer of copper appears on the surface of the substrate and the granules. With further heating to 850–889°C/1562–1632°F, depending on the alloys of the metals used, the copper fuses with the gold or silver surface and a new alloy with a lower melting point is formed on the surfaces of the component parts. This is necessary to initiate the diffusion process and to establish the metallic connection between the granules and the substrate.[1] Only the surface of the metal melts, causing the balls to connect to the base in a few critical seconds. (Figure 1)

The Finnish specialist in goldsmithing techniques, Oppi Untracht, describes this extremely difficult moment with the beautiful term “the moment of truth.”[2] A minimal amount of metal from the granules and the substrate form the “neck” between granule and substrate[3] (Figure 2). The correct ratio between energy and time, between the heat and the duration of heating is crucial here. If the heating is not enough, the granules will not be sufficiently connected to each other and to the substrate. Too much heating will melt the granules into each other and into the substrate. Perfect coordination between the eye, the hand and the flame is, therefore, of great importance at this point of the process. The joining phase takes the least time of the entire process of granulation, but at the same time it is certainly the most difficult and can only be carried out properly if the two previous operations, the making and the application of the granules, are carried out with sufficient accuracy.

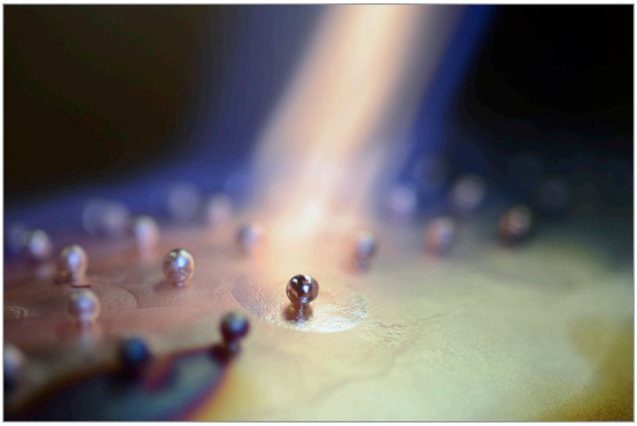


Figure 1 *Reaction soldering of the granule with the surface in a few critical moments: sterling silver base, sheet 0.8 mm (20 ga), fine silver granule 2 mm (.078 in.)*

Figure 2 *The neck between granule and surface: sterling silver base, sheet 0.8 mm (20 ga), fine silver granule 2 mm (.078 in.)*

Decorative Granulation on Silver Hollowware

Although the granulation process on larger silver hollowware does not differ much from traditional gold granulation on small objects and jewelry, it remains a rarity. Some of the reasons are surely the technical difficulties caused by the differences in size and material. The case presented here discusses experiments and results of fine granulation on larger silver objects.

The first piece examined, Object #1, is a sterling silver vessel raised from a round sheet with a 50 cm (19.68 in.) diameter and a thickness of 0.8 mm (20 ga). The object is cylindrical with a rounded base, diameter of 20 cm (7.87 in.) and height of 30 cm (11.81 in.). The weight is 1650 g (3.63 lbs.). It is decorated with approximately 5,000 fine silver granules of 2 mm (.078 in.).

The second piece, Object #2, is a sterling silver vessel raised from a round sheet with a 50 cm (19.68 in.) diameter and a thickness of 1 mm (18 ga). The object is completely spherical and has a diameter of 28 cm (11.02 in.) and a weight of 2100 g (4.62 lbs.). It is decorated with roughly 9,500 fine silver granules of 1.4 mm (.055 in.).

Technical Process

In order to establish a metallic connection between a granule and a surface via reaction soldering, it is necessary that a certain amount of copper is present in the connection zone and that the joining takes place in a reducing environment. Working with a mixture of organic adhesives and copper salts such as described above, the process works well with small gold jewelry. The mixture not only serves to create the reducing atmosphere and to establish the connection, but also to temporarily glue the granules in place on the surface. However, initial experiments to granulate silver with the use of organic adhesives and copper salts were not successful.

Another method examined is applying the copper directly to the granules and the recipient via galvanic copper plating. This method ensures that the copper is directly present on the material to be granulated and no longer needs to be added in the form of copper salts in order to transfer to metallic copper via reduction. With this electroplating method, the amount and thickness of the copper layer can be precisely calculated and controlled, mainly depending on the size of the granules.

Fully pre-copper plating the granules and the substrate also has some disadvantages compared to the conventional method because here the excess of copper that is not in the connecting zone between the granule and that surface cannot be removed. The surface of the granules will, therefore, not only melt at the points of contact but will sweat completely.

To be able to make a metallic connection via granulation, all elements (object and granules) need to be heated at the same time until the required temperature is reached to start the diffusion and make reaction soldering possible. In the case of decorative granulation on a silver hollowware object, the least obvious and (until now) unimaginable method is to heat it all in a kiln. Since the granules are not glued onto the surface, the little balls will roll off as soon as the object moves. Presuming the piece should be decorated all over the surface, it becomes a real mission impossible. Imagine it is possible to have it all in the kiln, the heating of the comparatively tiny granules will happen too fast. They will quickly come to their melting point and melt away while the surface of the object will not be warmed up enough to make the connection. A final remark about granulation in the kiln is that action and reaction related to the "moment of truth" happens indirectly. The object cannot be taken out when things go wrong, and adjusting granules that have moved is not possible.

Taking all this into consideration, it was decided to heat the object and granules with a large propane/compressed-air flame, traditionally used for annealing and soldering silver hollowware. Using the torch in the "right" way allows to bring only a very small area to the required temperature for granulation.

Object #1: Decorative Granulation in an Open Structure

Granules are blown away very quickly when using a large powerful flame, which is needed to heat up the surface of the object to make the reaction soldering happen. To keep the granules in place during the heating, little cylinders or jump-rings of titanium are prepared to encircle the granule (Figure 3). The granule stays in the ring until the connection is made. Titanium can resist very high temperatures and does not melt away or stick in the molten surface at the moment of granulation. At the same time, the little cylinder protects the single granule a bit from immediate contact with the flame. Ideally, the sphere is brought to the right temperature through the heat of the base metal, which is the best method for soldering small particles on larger objects.

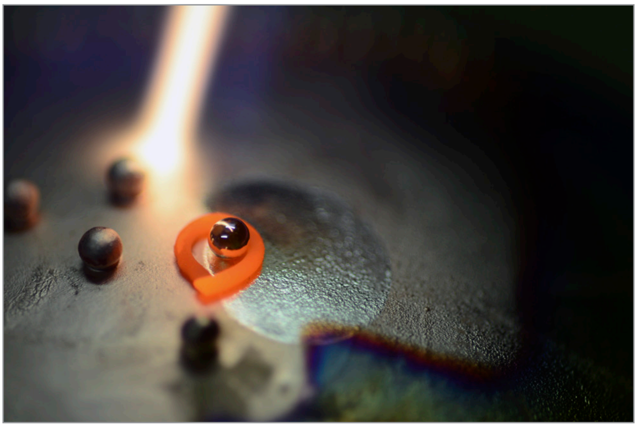


Figure 3 *Titanium ring keeps the granule in place during reaction soldering: sterling silver base, sheet 0.8 mm (20 ga), fine silver granule 2 mm (.078 in).*

To cover the surface of 1,962 cm^2 (304.11 $in.^2$) with roughly 5,000 granules, the pattern is built up gradually. After putting about five granules in place, using the titanium rings every time, the reaction soldering is done. Then another five and so on until the whole surface is covered, which means that the object is heated up about a thousand times. In this very long and repetitive process, the advantage of dry granulation becomes clear. There is no need to clean the object between the firings. This way the surface can stay warm and the granulation process can keep proceding without interruption.

While doing the granulation, there is significant difference in difficulty depending on the placement on the vessel. It is more difficult on a cylindrical area than on a spherical surface, which spreads the heat better in all directions. It also becomes more difficult closer to the edge since the edge heats up very quickly, with a serious risk of melting the surface too much. In order to fill the whole surface with granules, the object needs to be rotated regularly. During the granulation process the granules that are already connected stay in place and do not roll off the rounded shape even though they are sometimes brought to the melting point again. The fragile equilibrium they are in, together with the metallic connection previously made, is strong enough to keep them in place (Figure 4).

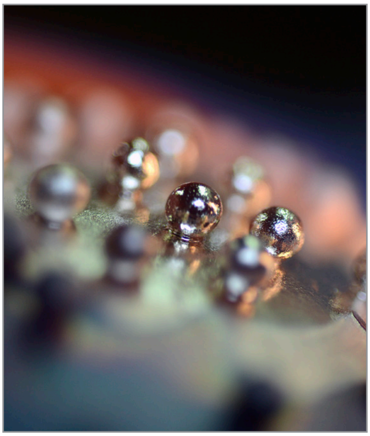


Figure 4 *Process of granulation on Object #1*

When all granules were put on, the object was not pickled to dissolve the copper oxide and become white silver again. Instead, the surface was left black oxidized and the layer of granules was highly polished (Figures 5, 6 and 7).

Figure 5 *Object #1: sterling silver vessel, diameter 20 cm (7.87 in.), height 30 cm (11.81 in.), approximately 5,000 fine silver granules 2 mm (.078 in.)*

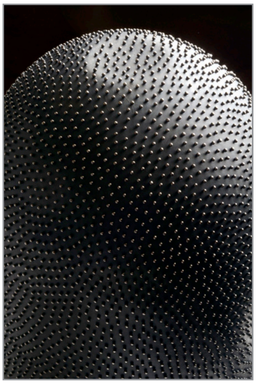


Figure 6 *Object #1, detail*

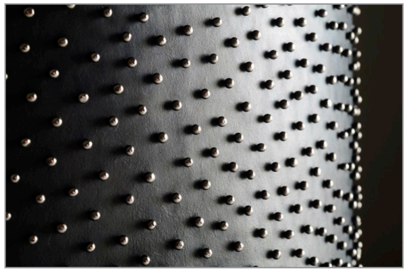


Figure 7 *Object #1, detail*

Object #2: Decorative Granulation in a Closed Structure

A multitude of individual granules can also completely fill spaces or larger surfaces. This space can be delineated by a wire or by the granules themselves. The case discussed here is a sterling silver spherical object of 28 cm (11.02 in.) diameter, with a granulated circle of 14 cm (5.51 in.) consisting of about 9,500 granules with a diameter of 1.4 mm (.055 in.). The position and the outline of the circle was decided in advance and subsequently copper-plated. The rest of the hammered object stayed white silver during the process. The pattern of the granules is created in a natural way, starting somewhere in the middle of the copper-plated circle (Figures 8 and 9). From there on the closed granulated structure "grows" toward the edge of the circle.

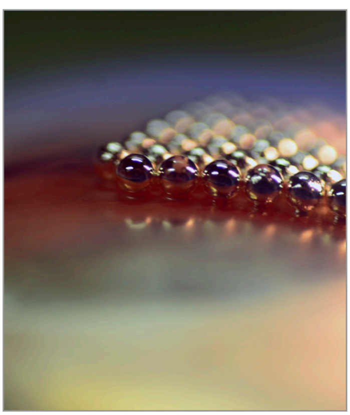


Figure 8 *Starting the process of granulation on Object #2*

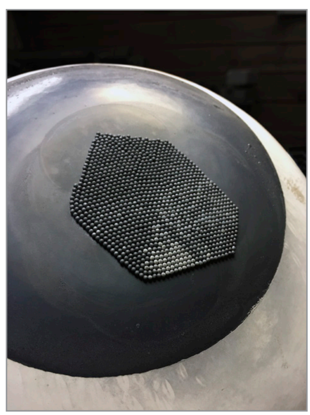


Figure 9 *Surface granulation on Object #2*

Using the huge flame in the “right” way makes it possible to heat very precisely. The melted spot on the surface gives the directions on how to move and adjust the flame to make the reaction soldering happen and connect the newly added granules with the surface (Figure 10).

The blowing and rolling away of the granules, as described above in Object #1, is not a major problem in this case. Only the first granules need to be kept in place. From the moment there is a fixed granulated area, the new granules can be positioned onto them. From that point it is only a matter of adding granules around the cluster until the circle is complete (Figure 11). Since the finished object is completely patinated dark, the subtle difference between the plain sheet of the substrate and the granular texture of the circle becomes more visible (Figure 12).

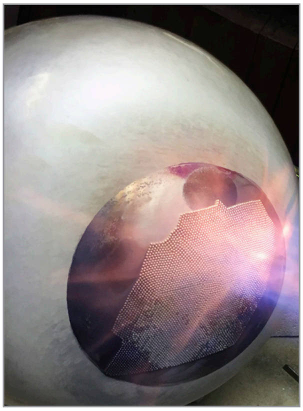


Figure 10 *The melted spot gives direction in the heating.*

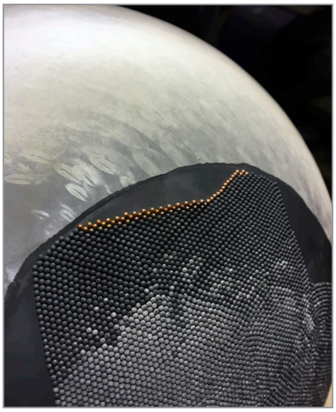


Figure 11 *New granules can be positioned on the already granulated structure.*

When identical granules are organized on a plain surface, they form pure geometric patterns based on the triangle and the hexagon. However, since the surface in this case is three dimensional, the granulated structure starts to show imperfections when it gets bigger and more spatial. The linear geometry is interrupted and, on the point of the imperfection, the same geometry starts in another direction (Figure 13). The American theoretical biologist and researcher of complex systems, Stuart Kauffman, speaks in this context about “order for free.”[7] This ability that spheres have to order and re-order themselves is also one of the reasons why, during the history of the art of granulation, one always discovers the same geometric structures based on the triangle and honeycomb pattern. These patterns are, therefore, not necessarily a signature of time or space, as ornamentation very often is, but the result of the self-organizing capacity of spheres.[4]

***Figure 12** Object #2: sterling silver vessel, approximately 9,500 fine silver granules*

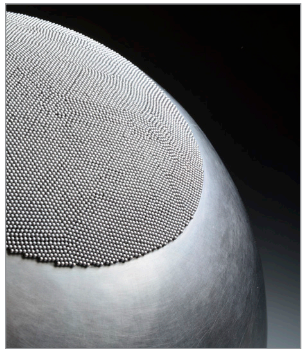


***Figure 13** Object #2, detail*

Structural Granulation—Introduction

Throughout the history of goldsmithing, the granulation technique has almost exclusively been applied to the surface of jewelry and small objects as an ornamental or figurative decoration. Jewelry pieces where the granules form the structural part are only found occasionally. The surface to which the granules are connected is generally flat or curved and only seldom is more than one layer of granules applied. Granulation is, therefore, essentially a graphic and pictorial, two-dimensional visual medium that makes it difficult to speak about its sculptural qualities. In addition, there are only a limited number of known examples of silver hollowware objects on which granulation can be found. From the combination of these two, namely the structural use of granulation and granulation on silverware, there exists no evidence and is apparently never used before in the centuries-long history of granulation art. This niche in artistic research, therefore, forms the point of departure for a body of work where granulation is the architectural support of the work and ornamentation at the same time. A few of the objects made in that context are discussed in the following section of this paper.

Since there is hardly any literature, referential pieces or research available on structural granulation and surely not in the realm of larger silver objects, the execution of these pieces can be compared with an experimental playground to discover the technical possibilities and limitations of structural silver granulation. Size and methods of making the granules as well as size and shape of the objects, the soldering methods and the formed structures of the granules were some of the researched subjects. Three spherical objects and their specifics are presented in Table 1.

Table 1 *Objects created with the use of structural granulation*

Object	Diameter	Height	Weight	# Granules	Granule size
Object #3	13.5 cm (5.31 in.)	13.5 cm (5.31 in.)	969 g (2.14 lbs.)	5,350	3.2 mm (.126 in.)
Object #4	26 cm (10.24 in.)	26 cm (10.24 in.)	3,012 g (6.64 lbs.)	16,550	3.2 mm (.126 in.)
Object #5	17 cm (6.69 in.)	17 cm (6.69 in.)	4,500 g (9.92 lbs.)	25,000	3.2 mm (.126 in.)

Technical Process

Constructing something only with spheres is quite problematic. Without extra support, spheres can only be stacked in a few formations and roll away the moment they are out of equilibrium. In traditional granulation, this problem is generally solved by gluing the granules on the surface before everything is heated and reaction soldered. Since, in this particular project, the granules build sculptural silver objects themselves, gluing the granules is not an option: first, there is no surface to be glued onto, and second, a structure created by gluing them to each other would collapse during the granulation process.

In order to build an object from thousands of little spheres, it appeared to be necessary to make a support or mold to place the granules on or in. An advantage of a concave mold is that, when the granules are put in, they automatically roll to the deepest point where the construction can begin. To create such a mold, a wax model of the object is made. Refractory concrete is applied in a thick layer around the wax model. After hardening the concrete and melting the wax, a perfect negative copy of the wax shape is created (Figure 14).

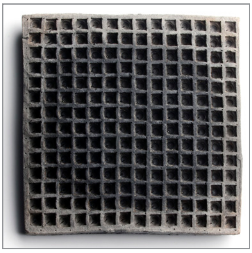
Figure 14 *Fire-resistant concrete mold, inside diameter 13.5 cm (5.31 in.), for making Object #3*

When a metal object, regardless of size or shape, is heated, it expands due to the heat and shrinks back to its original dimensions after cooling down. In other words, a silver granulated object is smaller before heating up and after cooling than during the moment of the actual granulation. For this reason, constructing a granulated structure around a positive form is very difficult. The object in progress would adapt perfectly to the shape of the mold during heating and granulation but would shrink and subsequently crack on the mold while cooling down, since the material of the mold is less subject to expansion than the already granulated metal structure.

In an object built only with granules, the joints should be strong enough to carry the weight of the final object, which in this project can be several kilos (pounds). To tackle that challenge, the granules are made bigger than traditional small-size granules. Larger granules make stronger connections and a stronger structure. The granules used in the three constructed pieces discussed here are sterling silver granules with a diameter of 3.2 mm (.126 in.). The production of these larger granules causes some problems when doing it in the traditional way, namely free floating in charcoal powder. Larger pieces of metal do not transform from a chip of metal into a sphere in one go. Consequently, in order to form useful granules, the pieces of silver would have to go in the kiln twice. This method would be enormously labor-intensive and, moreover, without certainty of a perfect result. In addition to this problem, these large and heavy balls often sink through the powder to the bottom of the crucible, resulting in a flattened granule.

In the literature about granulation, one can find the suggestion of making a cavity in a charcoal block to avoid the above described flattening of larger granules. A piece of metal is placed in this cavity and heated with a flame to the melting point. Due to the same phenomenon described earlier, the metal forms a sphere, a principle that is also called "shotting."[8] Because the metal is not melted on a flat surface but in a small concave bowl, it has no flat bottom side and, under the right conditions, a perfect sphere is formed. This principle works well for the production of single granules. For making a large number of granules, it is too time-consuming since every granule should be heated individually. Another downside of it is that the liquid metal can still absorb oxygen, which makes this technique unsuitable for silver granulation. A combination of the cavity and the charcoal powder principle is suggested as a solution.

A specific system was developed for this, whereby the granules are formed in pre-made cavities in a reducing atmosphere. Clay tiles (Figure 15) were produced where cavities are pressed into the upper surface by means of a round punch. The diameter of the desired granule determines the diameter of the cavity and of the punch, considering the shrinkage of the wet clay and the shrinkage of firing the tile. The depth of the pressed cavity is of less importance but must be at least half its diameter so that the largest diameter of the granule, the "equator," remains below the edge of the cavity. In order to have the piece of metal slide down when the sphere-forming process starts, the top edge of the pressed cavity is chamfered. After the tiles are fired, pieces of silver with the same volume as the desired granules can be placed above the cavities (Figure 16).



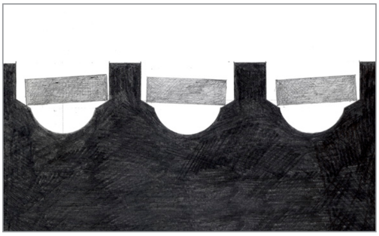


Figure 15 *Ceramic tile for granule production, 9.5 cm x 9.5 cm x 1.0 cm (3.74 in. x 3.74 in. x .39 in.).*

Figure 16 *Drawing of cross section of ceramic tiles for granule production*

When the tile is filled with little silver coupons (Figure 17), it is placed on the bottom of a flat refractory crucible, covered with a piece of thin paper and filled with charcoal powder. The paper serves as a protection to prevent the charcoal powder from ending up between the granules and the cavities, which would deform the granules (Figures 18 and 19). The crucible is finally closed with a stone lid and put into the kiln, fired up to about 100°C (180°F) above the melting temperature of the silver (Figure 20). The little plates transform into little spheres and sink in the cavities (Figures 21 and 22). During the firing process, the charcoal powder and the paper burn away partially and create a reducing atmosphere inside the crucible (Figure 23).

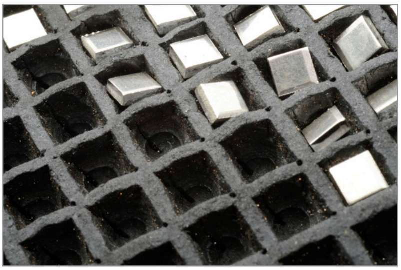


Figure 17 *Ceramic tile for granule production: sterling silver coupons, 3.7 mm x 3.7 mm x 1.25 mm (.146 in. x .146 in. x .049 in.)*

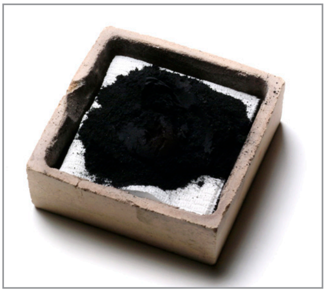


Figure 18 *Filled ceramic tile is placed on the bottom of a flat refractory crucible.*

Figure 19 *Filled ceramic tile is covered with a piece of thin paper and charcoal powder.*

Figure 20 *Filled crucibles are closed and put into the kiln.*

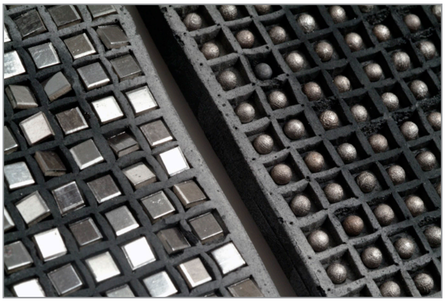


Figure 21 *The little coupons transform into spheres in the ceramic tiles.*

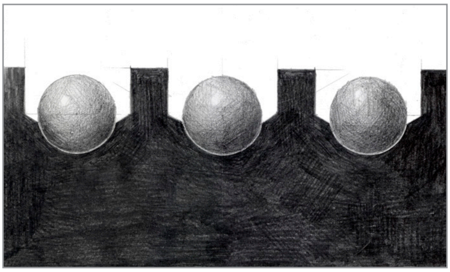


Figure 22 *Drawing of a cross section of ceramic tiles for granule production*

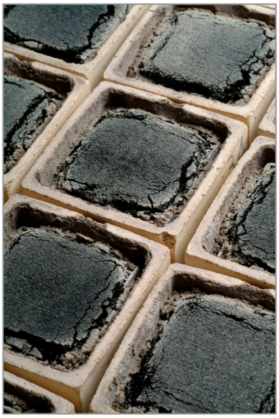


Figure 23 *The charcoal powder burns away partially to create a reducing atmosphere inside the crucibles.*

Because the mass that goes into the kiln is so large, heating up and especially cooling down takes a lot of time. Due to the slow solidification of the metal, the crystal structure of the granules is very coarse and clearly visible to the naked eye (Figure 24). For this reason, the rough granules, after being removed from the tiles and crucibles, are polished for several hours in a polishing drum, resulting in perfectly round, smooth and shiny silver granules (Figure 25).

Figure 24 *Granules (sterling silver, 3.2 mm/.126 in.) are coarse due to the slow solidification process.*

Figure 25 *Polished sterling silver granules in Figure 24*
:

To obtain perfectly round granules, it is of course crucial that the cavities in the tiles have the correct dimensions. Cavities that are too small will create mushroom-shaped granules. On the other hand, if the volume of metal is too small for the cavity, the spherical radius of the granule will be flatter at the bottom than at the top. Finally, it is necessary to state that the maximum size of the granules produced by this method is also limited.

Because, as mentioned above, the process of electroplating the granules works very well, resulting in granulation with nice, smooth joints, the same process of copper-plating is also used in this granulation construction.

In contrast to the previous stages in which the granules are manufactured and copper-plated, the placement of the granules is not done in one go. Therefore, putting the granules in the mold is constantly alternated with the reaction soldering itself. Each time, a limited number of granules is granulated, ranging from one to twenty, depending on the type of object and on the construction phase the object is in.

Object #3: One-Layered Structural Granulation in a Closed Structure

When the first copper-plated granules are placed in the mold, they behave as if they are lying on a flat surface. They are not pressed against each other and sometimes tend to roll away from each other because of an irregularity in the mold or through the force of the flame during the firing. Since the granules need to touch each other in order to be connected via reaction soldering, small triangles of, for example, ten granules are prepared. Subsequently, this triangle is not placed on the bottom but on the sloping side of the mold so that the following granules roll against this support and the building of the object can start (Figures 26 and 27).

Figure 26 *Pre-granulated form to start building Object #3*

Figure 27 *Object #3 in progress; the pre-granulated triangle "grows" further.*

During the making of the object, it is necessary to heat up the already granulated structure where the new granules are added; this is to prevent the new ones from melting before they are connected. Note that it is important to prevent the copper on the surface of the granules from oxidizing by working with a reducing flame. Using an oxidizing flame will change copper into copper oxide and the soldering process will not take place. A constant search for the best flame, the right ratio in the gas/oxygen (or compressed air) mixture and a flame that is nevertheless hot enough but also sufficiently reducing is necessary for successful granulation. Furthermore, it is essential to slowly move the flame back and forth over the granules because it is difficult to estimate the temperature through the flame. At the same time, this results in gradual heating of the already granulated structure and of the new granules.

With a properly adjusted flame and after sufficient heating, the surface of the granules will first start to "sweat," creating a soft shine on them. This is the moment before the reaction soldering takes place and the granules are joined at their points of contact. Just like with traditional granulation, a combination between the right temperature, the right flame and the right duration is crucial for achieving an ideal joint (Figure 28). From this point on, granules are added and granulated until the edge of the mold is reached and a half-spherical bowl is created.

Figure 28 *Object #3 in progress*

Huycke

Because the shape of the mold is identical in all places, the granulated object can rotate in the mold as a ball and socket. Thanks to this possibility, one side of the edge of the granulated hemisphere can be placed deeper in the mold and new space is created to continue building. The bowl can now grow further and become higher than a hemisphere. With Object #3 the aim was to make it as high and closed as possible with the smallest possible opening. The difficulty is that as the hole in the top becomes smaller, there is no longer room for the torch. Eventually, there comes a point where working from the inside of the bowl becomes impossible. A solution was found in the use of a spherical plate (with a radius identical to the inside of the object) made of stainless steel. By clamping this plate on the inside of the object, the granulation can continue until the spherical object is finished (Figure 29). The diameter of the minimum opening of the object depends on the size of the plate and on the possibility to get the plate out again when the structure is finished.

Figure 29 *Object #3 in progress: A stainless steel plate is clamped to the inside of the granulated structure to make it possible to work from the outside of the object.*

Figure 30 *Finished Object #3: sterling silver granulated object, diameter and height 13.5 cm (5.31 in.), with approximately 5,350 granules of 3.2 mm (.126 in.) diameter*

Object #4: One-layered Structural Granulation in an Open Structure

To make the walls and structure of Object #4 more transparent to obtain a lighter effect, the self-organizing nature of the granules needed to be altered. Modules of two granules (Figure 31) were produced as construction elements that would form a "bridge" over a curve of four granules where normally one granule would fit perfectly. By repeatedly making the same action with the "bridge," a system was created with an ordered but more open and lighter configuration (Figure 32). In a closed structure a "flower" of six granules with a seventh in the middle is formed, whereas in an open structure, the center ball is absent, forming a hexagon of six granules. Each granule in the structure also serves as a part of the hexagon that comes next to it. A structure made up of identical hexagons is only possible in a flat plane. In a three-dimensional shape, the hexagons are occasionally alternated with pentagons and irregular shapes. The technical execution of this object proceeds in the same way as with Object #3. In this case the object is larger, has an open structure, and was pickled to make the silver white again..

Figure 31 *Module of two granules for creating an open structure in Object #4: sterling silver, diameter 3.2 mm (.126 in.) x 6.4 mm (.25 in.)*

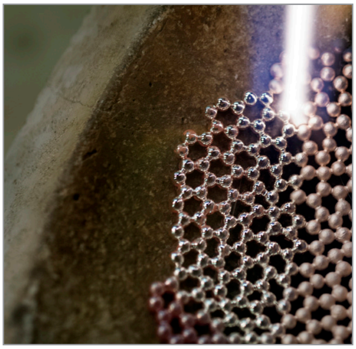


Figure 32 *Object #4 in progress: process of granulation in the open structure*

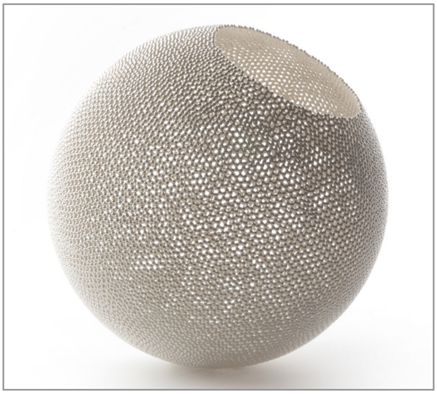


Figure 33 *Object #4: sterling silver granulated object, diameter and height 26 cm (10.23 in.), approximately 16,550 granules of 3.2 mm (.126 in.) diameter*

Figure 34 *Object #4, detail*

Object #5: Multi-Layered Structural Granulation in a Chaotic Structure

Challenging the phenomenon of self-organization takes shape in Object #5. In order to achieve a state of chaos in a granulation structure, a thought-out stacking method must be introduced. It seems paradoxical that this effort must be applied according to a logic system, stronger than the natural urge for self-ordering of the granules. The method used in Object #5 consists of stacking modules of three interconnected granules (Figure 35). In contrast to the single and double sphere, this configuration does not roll away when placed, making it possible to position the granules randomly, apart from the already created structure.

Figure 35 *Module of three granules for creating a chaotic structure in Object #5: sterling silver, 3.2 mm x 5.0 mm x 8.6 mm (.126 in. x .197 in. x .339 in.)*

Initially, a granulated bowl is created that fits precisely into a mold with 16 cm (6.30 in.) inside diameter. On the inside of the bowl a structure of the three-granule modules is granulated in the most chaotic way possible. Consequently, another chaotic layer is granulated on the outside of the bowl to make a three-dimensional structure producing an object that has an irregular structure on both the inside and the outside surface, built up from multiple layers of granules. To complete the object from a bowl shape towards a spherical object, the edge is raised up gradually with the modules of three granules. Because of the heavy weight of the piece and the large amount of silver granules, building up the object is more challenging and dangerous than with the previously made objects. It takes much more time to get the object warm enough to make reaction soldering possible, which increases the risk of the granules melting into each other. In addition, during the whole building process, the hot glowing mass of silver radiates lots of heat and light, making it hard to place the new granules over and over again and to clearly evaluate the moment of fusion (Figure 36).

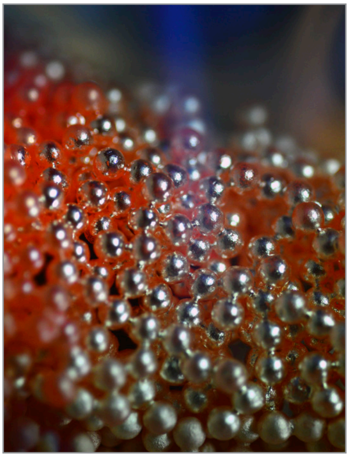


Figure 36 *Granulation process of Object #5*

Figure 37 *Object #5: sterling silver granulated piece, diameter and height of 17 cm (6.69 in.) with approximately 25,000 granules of 3.2 mm (.126 in.)*

Figure 29 *Object #5, detail*

Conclusion

It goes without saying that this kind of work requires very good control and coordination between the eye, the brain and the hand and is executed in an all-absorbing concentration. While shaping an object via structural granulation or decorating it with surface granulation, the risks of meltdown and collapse are real until the piece is finished. Time and again, working on the dangerous brink between the possible and the impossible, just before the surface sheet completely melts or the spheres melt down into each other, is the essence and the moment when the object comes into existence. In this tedium of slowness and endless repetition, the risk of failure concentrates the mind.

References

1. Jochem Wolters, *Die Granulation: Geschichte und Technik einer alten Goldschmiedekunst*, 2nd ed. (Munich: Callwey Verlag, 1986).
2. Oppi Untracht, *Jewelry: Concepts and Technology* (London: Robert Hale Limited, 1985).
3. Diane Lee Carroll, "A Classification for Granulation in Ancient Metalwork," *American Journal of Archaeology* 78 (1974): 33-39.
4. Gerhard Nestler and Edilberto Formigli, *Etruskische Granulation: Eine antike Goldschmiedetechnik* (Sienna: Nuova Immagine, 1993).
5. J. Hammes, *Goud, zilver, edelstenen* (Amsterdam: De Technische Boekhandel H. Stam, 1944).
6. Jack Ogden, *Jewellery of the Ancient World* (New York: Rizzoli, 1982).
7. Stuart Kauffman, *At Home in the Universe: The Search for the Laws of Self-Organization and Complexity* (New York, Oxford: Oxford University Press, 1995).
8. Thea Politis, "Gold and granulation: exploring the social implications of a prestige technology in the Bronze Age Mediterranean," *The Social Context of Technological Change: Egypt and The Near East, 1650-1550 B.C.*, ed. Andrew J. Shortland (Oxford: Oxbow Books, 2000): 161-194.