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Old Process, New Technology: Modern Mokume Gane

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Introduction

Mokume gane is one name for a metal-working technique developed in Japan approximately three to four hundred years ago, in which two or more layers of metal are permanently joined together in alternating layers to form a stack (or billet). In the traditional Japanese technique the bond was achieved by diffusion welding of the layers in a charcoal forge. On this laminated billet, patterns of the different colored alloys were created by a combination of cutting, twisting and forging of the laminate in ways to expose the various layers. The patterned billet was then formed into finished work by applying standard forging and fabrication techniques.

The name "mokume gane" refers to the visual appearance of pattern in metal approximating that of wood. "Mokume" literally means "wood eye," which would be used to describe a highly figured wood grain. "Gane" translates as metal. So, in English, "wood grain metal" is a near-literal translation.

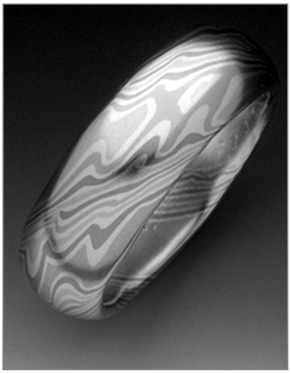

Figure 1 *Ring, 18K yellow, 14K red and 14K palladium white golds and sterling silver by James Binnion, 2000*

In making mokume gane, the craftsman selects alloys for various properties. The most significant characteristics of a prospective metal are color and malleability. Color considerations include not only the natural bulk color of the metal, but also various patinas that can be developed by application of chemical agents and/or heat. Depending on the amount of material being made and the pattern desired, the sheets are prepared in thicknesses ranging from foil to plates of more than 0.25 inch. They are cut to the same shape and cleaned very thoroughly to remove all dirt, oils and (most importantly) oxides. After being stacked and bound together to ensure intimate contact over the whole of the adjoining surfaces, the billet is heated in some way to create a bond. Depending on the particular technique employed, the bond might be a solid-state diffusion weld, a transient liquid-phase diffusion weld[1], or a liquid-phase diffusion weld of the individual sheets into a laminated billet. The laminated billet is forged to strengthen the weld and to reduce its thickness before patterning.

Patterning consists of exposing layers from within the billet on the surface. This may be accomplished by any of several methods. Carving into the laminated surface with chisels or rotary tools, then either flattening the whole carved billet to a uniform thickness or leaving it as a relief pattern would be one way. Punching or stamping from either the front or back side and then scalping the surface down to a uniform level with files or by milling is another. Exposing the end grain of the billet by twisting or forging on end is a third. Many interesting possibilities are opened up by re-lamination of patterned material to create complex patterns or mosaics. This is where technique and art meet. The limits to patterning exist solely in the artist's mind.

History of Mokume Gane, Late 1600s–Mid 1900s

The sword was one of the main areas of decorative metalwork in feudal Japan. Some of the finest and most skillfully wrought metalwork in the world was used in the creation and outfitting of many of these swords. The innovation of this decorative technique is attributed to Denbei Shoami (1651–1728), a master smith from Akita prefecture.

> Shoami's first piece is comprised of layers of copper and shakudo (a Japanese copper alloy that contains 2.5% to 4% pure gold) laminated to create a tsuba (sword guard) that was carved and flattened. The effect is similar to Chinese and Japanese lacquer work known as quiri-bori "where thick parallel layers of alternating red and black lacquer are built up to a considerable thickness and grooves are deeply incised to expose colored lines on their sides."[2] Shoami gradually learned to flatten and to produce wood-grain patterns that lie on the surface of the laminated mass.[3]

It is likely that Shoami developed mokume gane by applying traditional forge welding techniques to the non-ferrous metals used to decorate and complete the sword. Many of the ferrous and non-ferrous mokume gane *tsuba* and other fixtures exhibit patterns that are similar to the patterns developed in the sword blades. He passed his technique down to other smiths, and there are several beautiful examples of mokume gane *tsuba* and other sword furniture that still exist in collections around the world today.[4]

Besides the sword smiths and makers of sword furniture, other metalsmiths learned to use the technique to make vessels and other objects. In his March, 1893, lecture for the Society of Arts, Professor W. Chandler Roberts-Austin describes one such object, a vase that is in the collection of the British royal family.

> ...the body of the vase is of mizu-nagashi, (marble-like pattern) consisting of alternate layers of shaku-do and red copper...[5]

Because of the great difficulty of its manufacture, mokume gane has never been a widely practiced technique. Though there were not a great number of mokume gane objects produced, some magnificent metal objects were exported to Europe and North America in the late 1800s. Those pieces caught the attention of scholars such as Roberts-Austin (above), and Raphael Pumpelly, who wrote what was probably the first English-language description of the process in 1866.

> Beautiful damask work is produced by soldering together, one over the other in alternate order, thirty or forty sheets of gold, shakdo, silver, rose copper, and gin shi bu ichi[a], and then cutting into the thick plate thus formed with conical reamers, to produce concentric circles, and making troughs of triangular sections to produce parallel, straight or contorted lines.[6]

Pumpelly's description of the layers being "soldered together" remained associated with the process well into the 20th century and caused great difficulty for western smiths trying to replicate the technique. Modern analysis of early mokume gane objects indicate that they were welded using diffusion techniques, not solder[1]. It is almost impossible to use soldered mokume gane to fabricate any object that requires significant deformation of the material in the manufacture of the item. This is due to the relative brittleness of most solder alloys, leading to the de-lamination of the soldered bonds during forming. This difficulty did not prevent some work from being done by this technique by western smiths. There were at least two western smiths who made work using mokume gane in the late 1800s and early 1900s. Both were influenced by the unique techniques and styling of the Japanese smiths. One was Sir Alfred Gilbert[7], who used mokume gane in the central link of the chain of office for the Mayor of Preston, Lancashire, England.

Another was Edward C. Moore, who was Louis Comfort Tiffany's chief designer in

[a]*gin shi bu ichi* is an alloy of copper and silver where the silver content ranges between 50% and 80%. It and a whole range of copper-based alloys are used in many Japanese metal objects.

the 1870s. Several mokume gane objects were made in Tiffany's workshops, including a coffeepot and flatware with mokume gane handles.

Old Sheffield Plate

The Japanese were not the only ones to develop techniques of diffusion bonding of non-ferrous metals. Thomas Boulsover also discovered diffusion welding of silver to copper alloys in England in 1743. A cutler in Sheffield, England, Boulsover is reported to have inadvertently bonded copper to silver on a knife haft he was working on.[8] He discovered that the bonded metals would elongate in unison when rolled. This discovery led to the production of a wide variety of Sheffield Plate items for the growing middle class consumer in England who could not afford solid sterling wares. The Sheffield Plate process for laminating is very similar to the Japanese mokume gane lamination. The main difference is that with Sheffield Plate there were normally only two or three layers, and during manufacturing they were very careful not to expose the inner copper alloy through the silver cladding. The smiths of Sheffield produced tons of this material between 1742 and 1855, at which time it was almost totally superseded by electroplating.[9]

There is no indication that the Sheffield Plate process was ever used to create decorative multicolored metal surfaces by cutting through the outer silver layers. It is of interest to note the different ways the same process was used by two different cultures. The Japanese used the lamination process to create decorative patterns using many different alloys of both precious and base metals, while the English used it to cover the base metal to give an appearance of preciousness.

Industrial clad metal products such as 14k gold-filled sheet and wire and the more recent 22k over sterling bi-metal are direct descendants of the Sheffield Plate process. There is still a demand for this type of product in the jewelry market today.

Modern Studio Mokume Gane

In the first half of the twentieth century, mokume gane was almost totally unknown in the west. Only scholars and museum staff such as Dr. Cyril Stanley Smith,[1,2,10,11] Herbert Maryon[7] and a small number of collectors[4] of Japanese metal work were aware of it. In Japan it was also nearly unknown. Between modern Japan's movement away from the traditional crafts and the small number of aging craftsmen practicing the art, it might totally have been lost.

It was C.S. Smith's analysis of antique sword blades and fixtures that brought ferrous and non-ferrous pattern welding to the attention of a group of metal artists at Southern Illinois University at Carbondale (SIUC). By the early 1960s, Professor L. Brent Kington and a group of his graduate students had embarked on a course of research and experimentation that began with bringing the arts of the blacksmith to academic art circles, and continued on to exploring the patterning of ornate Asian, Islamic and European blades in iron.[12]

This inquiry naturally led to experimentation attempting to replicate the mokume gane found in items in museum collections. Many methods were tried, from soldering to immersion of a solid in a molten metal. When bonding by these methods, a "large" billet was 1/2" square by 1" long, and loss rates of 90% were not unusual. Esoteric references in blacksmithing lore and literature to the forge welding of copper by traditional blacksmithing techniques led to a pivotal change in methods. In the words of Professor Kington, "a light went on in my head."

Concurrently, Hiroko Sato Pijanowski and Gene Pijanowski, who are instructors and metalsmiths with interests in traditional Japanese metalworking techniques, saw a mokume gane vessel while visiting Japan in 1970.

> ...we viewed the annual "Traditional Craft Exhibition" at Mitsukoshi department store in Tokyo. There we saw a raised mokume-gane pot by Gyokumei Shindo. It was beautifully executed having a surface effect of polished marble, but with none of the technical and physical limitations of laminating nonferrous metals with silver solder. Since then we have been fascinated with mokume-gane.[3]

This fascination lead to another trip to Japan to work with Norio Tamagawa, a skilled craftsman in the traditional form of mokume gane. The Pijanowskis returned to the States and started publishing papers[3,13] about their research into the mokume gane technique and teaching workshops to spread their knowledge of this technique.

These parallel pursuits were bound to intersect. In the spring of 1977, the Pijanowskis were invited to SIUC for a weekend visiting artists' lecture and workshop. They shared their knowledge of Japanese alloys, patinas, and methods. The Carbondale group shared their understanding of the applications of the blacksmiths' art.[14] A significant innovation from SIUC student Marvin Jensen was the use of "torque plates" to compress the stack during the laminating process. The torque plates consisted of two mild steel plates approximately one-quarter to one-half inch thick that were drilled around the perimeter. Four to six bolts were passed through the holes and tightened or "torqued" down to provide greater pressure on the sheets during lamination than the heavy iron wire used by Tamagawa and the Pijanowskis. This increased contact pressure and reduced the time required to prepare the sheets. They no longer needed to be ground perfectly flat, since the tightening of the bolts removed small irregularities in flatness of the sheets. This innovation greatly improved the success rate of the lamination process.

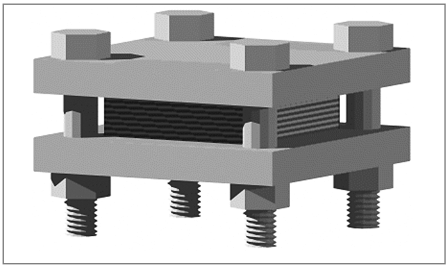

Figure 2 *Torque plates*

In the winter of 1982, a masters workshop was held at SIUC to teach mokume gane to academic art instructors with the intention of spreading the knowledge of the technique to the art metalsmithing community. This sharing of knowledge in the publication of the research papers and workshops by the Pijanowskis and their students, the SIUC research team, and others has lead to a growing interest in mokume gane by designers, art jewelers, metalsmiths and the public. Goldsmith Steve Midgett[15,16] has published two books and one instructional video on mokume gane, which have helped to increase interest in and understanding of the technique. One of the SIUC graduates, Philip Baldwin, asserts, "There are more people in the USA working in mokume gane at this time than there ever were in Japan."

The method of lamination that the Pijanowskis describe[13] is a liquid-phase diffusion weld. After thorough mechanical and chemical cleaning, the metal sheets are stacked and bound between iron plates that have been coated with a resist to prevent the laminate from sticking to them during the diffusion process. The stack is placed in a forge and heated until the metals in the stack begin to "sweat." At this point some of the alloys in the stack have reached the temperature where some liquid phase is visible on the edges of the stack. The stack is quickly and carefully removed from the forge and "lightly tapped with a wooden mallet." It is then hot forged to improve the bond strength and reduce its thickness. In the published papers (with the exception of some early unsuccessful and marginally successful experiments with an electric kiln as the heat source) the lamination process was carried out in either a coal, coke or charcoal-fired forge or a gas-fired kiln; all of which provide the reducing atmosphere which is necessary for a successful lamination. Because these papers were exploring methods for the studio craftsman, industrial heat sources like controlled atmosphere kilns were not used.

Exploration of the Electric Kiln for Laminating Mokume Gane

The coal forge or gas-fired kiln technique explored by the SIUC graduate students and the Pijanowskis worked well for studios equipped with them but was not really viable for the typical goldsmith, who would have neither a forge nor a place to install one.

In the published papers on mokume gane, most references to the electric kiln report significant problems[13,14,17] with the oxidizing atmosphere encountered in the electric kiln. In the presence of oxygen the majority of metals used in mokume gane will develop oxide films that will inhibit the diffusion weld. In a heated environment like the kiln they grow very rapidly and tend to penetrate into the stacked layers, causing an incomplete bond. Two methods were cited in the published papers to create a reducing atmosphere around the laminate in the kiln.

One involved placing hardwood charcoal in the kiln chamber along with the stack, in effect creating a forge environment in the electric kiln. This proved successful as far as the laminate was concerned, but the reduced visibility in the kiln made the forge a much easier method if one was available. There are other problems in packing the kiln with charcoal that are not discussed in any of the papers: the production of significant amounts of carbon monoxide from heating the charcoal in the presence of oxygen, and the greatly reduced life of the heating elements due to the effects of the reducing atmosphere in the kiln.

The second method involved coating the edges of the stack with hide glue with the idea that the glue would carbonize and provide the desired atmosphere at the edges of the laminate. However, the glue coating tended to crack during firing, leading to uneven results. Several additions were made to the glue to try to keep this from happening, none of which were reported to be successful.

In reading the papers that discussed attempts to laminate in an electric kiln, it appeared there were two basic problems encountered: lack of temperature control, and the oxidizing atmosphere present in the kilns used for the tests. In 1983, experiments were begun by James Binnion to explore whether using an electric kiln for laminating mokume gane was a viable alternative to the use of the forge.

Most small kilns of the type found in the goldsmith's studio have power level controls that adjust the amount of electric current applied to the kiln's heating elements. This type of control does not regulate the temperature in the kiln. It sets the amount of energy being supplied to the kiln, but the actual temperature within the kiln will depend on a number of variables, such as: the quality of the insulation of the kiln, the external air temperature, air currents and how much electrical current is being used by other devices on the same circuit. As a result, setting and holding a precise temperature is almost impossible. To solve this problem, a temperature controller is required. Commercial industrial temperature controllers available in the early 1980s typically used discrete components, so they were fairly large and the cost was several times the price of one of these small kilns. At that time advances in integrated circuit technology and power control semiconductors made it possible to build an analog proportional controller capable of regulating temperature to within a few degrees fahrenheit using only a handful of components. Such a controller was built and added to a small electric kiln. With a working chamber of 4.5" x 9" x 4.5", this kiln was typical of the kind found in many small goldsmiths' studios. The proportional controller was a great improvement over the power level–type controls. The precise temperature control greatly reduced the likelihood of over firing and melting the laminate.[b]

Once the temperature controller was satisfactorily tested on the kiln, experiments were undertaken to try to address the issue of the oxidizing atmosphere. Cleaned stacks of copper and brass were bolted between torque plates and then coated with hide glue and one of several additives to see if the glue could be made to act as an oxygen shield around the stack. The first attempts involved mixing fine mesh charcoal with the hide glue to try to increase the amount of solids in the glue to reduce the cracking during firing. The billet was then fired for two hours at 1500°F. The charcoal addition did not seem to change the cracking of the coating, and the resulting laminate required significant trimming of the edges to remove the oxidized material. The second set of attempts involved adding borax to the glue mixture to try to form a flux glass seal around the stack. A coated stack was fired for two hours at 1500°F. The resulting laminate again had significant amounts of oxide penetration between the layers, and the oxidized areas had to be removed before proceeding.

After several attempts at making a coating that would not crack and burn away during the firing of the stack, a new method was tried. An enclosed chamber was created around the laminate by wrapping 26-ga. steel sheet around the perimeter of the torque plate stack and filling the void between the stack and the steel sheet with charcoal. This box around the stack was first tried with the edges of the stack coated with glue, as well as with charcoal inside the box to provide a reducing atmosphere around the stack. After firing, the laminate was examined.

[b]Today, digital temperature controls are readily available at reasonable prices. In some low-cost units, the temperature controllers are already incorporated into the kiln by the manufacturer.

It had minimal oxide problems and resulted in a useable laminate that was at least 50% larger than using the hide glue alone.

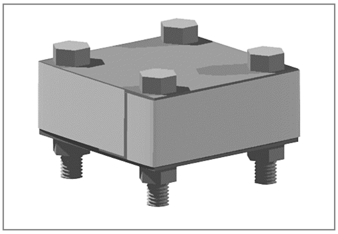

Figure 3 *Steel sheet-wrapped torque plates*

It was noticed that sometimes there would be non-laminated areas that looked like a liquid had been drawn into the areas between the layers. This would be normally around the edges of the stack. It seemed as if water from the hide glue was being drawn in between the layers of the stack in the early stages of the process, before the heat of the kiln drove off the water. A laminate was prepared without the hide glue, but still surrounded by the charcoal in the box. After firing and removal from the torque plates it was found to require as little if not less of the edge material to be removed after firing as similar billets fired with the hide glue. Over time it was found the billets fired without the hide glue exhibited fewer edge problems than the ones with the glue. It became apparent that the glue was actually detrimental to a complete bond of the stack.

With increased firing times, the charcoal enclosed in the box would often totally burn away. This was due to the incomplete seal created by wrapping the steel strip around the edges of the torque plates. A search for a material that could withstand the environment of the kiln and also provide a good seal to keep the oxygen out was begun. Such a material was found in the heat-treating industry: a 0.002"-thick, Type 321 stainless steel foil. It can withstand temperatures in excess of 1600°F and is easily formed by hand. Using this foil one can make a relatively gas-tight bag by folding and burnishing the seams closed. The torque plates and stack are placed in the bag and the bag is filled with charcoal and sealed. This produces a strong reducing atmosphere in the bag when placed in the kiln.

Liquid-Phase Diffusion and Solid-State Diffusion

One of the reasons mokume gane is such a difficult technique to master is that the judgment required to know when the billet is laminated requires quite a bit of experience to develop. In the forge it is possible to use visual cues to help with this. As the Pijanowskis suggested, one can wait until the low melting point alloys begin to weep or sweat before removing the billet from the forge and this will produce a liquid-phase diffusion bond. It is also possible to use the SIUC method of using a steel probe to scratch the surface of the edge and look for a shine or flash that will indicate the presence of the liquid phase before it actually starts to weep out of the stack. The second method probably provides more safety margin because if one does not act quickly, there will be too much liquid phase present and the alloy may lose its cohesion and ruin the laminate. This is especially true if any of the metals in the stack that are in contact with each other form a eutectic alloy. If the temperature exceeds the liquidus of the eutectic during the lamination process, the metals will tend to form the eutectic alloy as they are attempting to reach equilibrium. The alloy at the interface between layers will lose cohesion and the remaining sheets will slip and slide in the liquid. This almost always results in having to scrap that billet. This makes learning to read phase diagrams an important skill for the craftsman, as these diagrams will show the presence of eutectic point(s), such as the one at 28.1% Cu on the copper silver phase diagram in Figure 4.

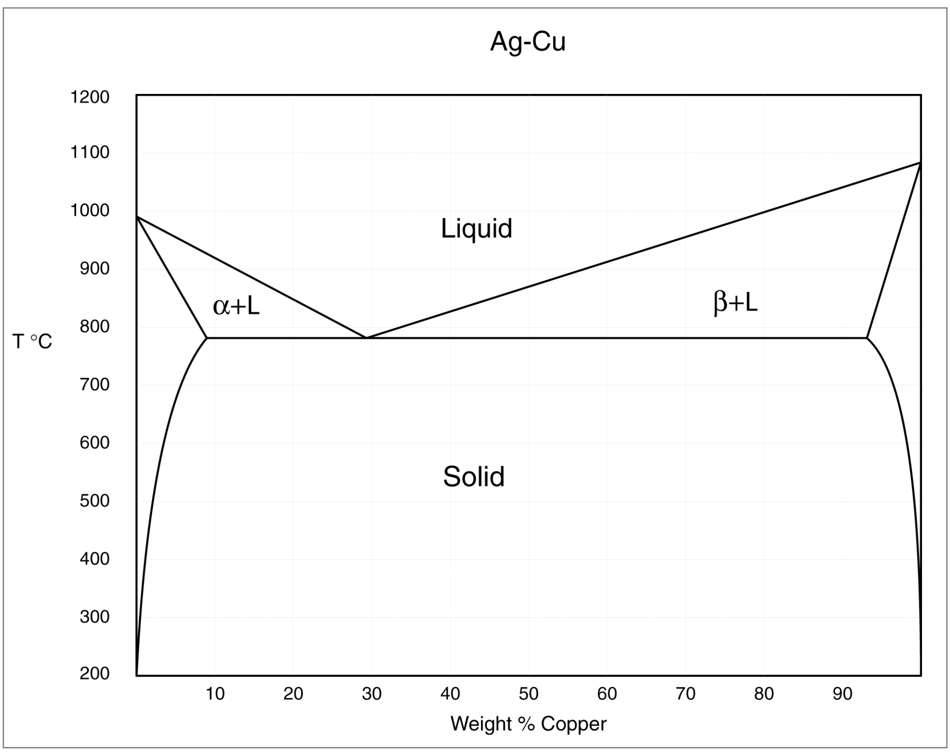

Figure 4 *Silver copper phase diagram*

Using visual cues to determine temperature of the laminate cannot be done when the stack is in a steel box or bag within the electric kiln. John McCloskey suggested in his paper[18] that calculating the proper temperature for liquid-phase bonding can be accomplished by the use of information contained in the phase diagrams for the alloy systems in use. In the past, most smiths would not have access to the data needed or the training required for making such calculations. Now the internet has provided access to a tremendous amount of information. A recent search of the internet provided binary phase diagrams[19] for most of the metals in use in decorative metalworking and even step by step instructions[20] on how to read them. Also, the recent publication of an English-language edition of Dr. Erhard Brepohl's *The Theory and Practice of Goldsmithing*[21] provides another source for gaining knowledge of basic precious metal metallurgy and the meaning and use of phase diagrams for the studio smith.

As an alternative to the liquid-phase welding process, lamination can also be achieved by solid-state diffusion welding. The preparation for solid-state lamination is identical to the liquid-phase technique. The difference is in the degree to which the stack is heated. To perform solid-state lamination, precise temperature control is required to hold the laminate at a temperature just below the point where liquid phases would begin to form. Diffusion will occur at a slower rate than in the liquid-phase bonding, but crystals will grow across the sheet boundaries, providing a bond between layers. To allow for the slower rate of diffusion, the laminate must be heated for longer times than in the liquid-phase process.

With the temperature-controlled kiln, tool wrap bags, the solid-state lamination process and experience, our success rate for lamination has increased to nearly 100 percent. We have applied this process for lamination to a variety of metals, including alloys of copper, gold, iron, palladium, platinum and silver, and have found that all the combinations we have tried will laminate. In applying modern technology to the ancient process of mokume gane, a system has been developed to produce a variety of laminates with a high success rate. This allows us to focus on the patterning and fabrication of decorative objects, rather than on the lamination process itself.

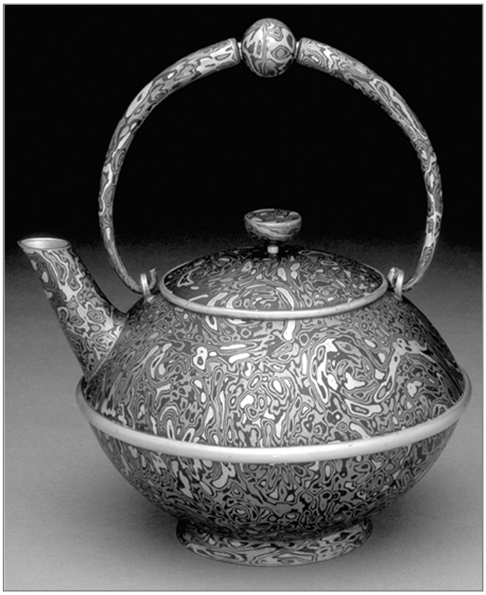

Figure 5 *Teapot. Copper, brass and sterling silver by James Binnion, 1998*

Figure 6 *Teapot, detail. Copper, brass and sterling silver*

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