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Present and Past of Southern Indian Crafts for Making Mirrors, Lamps, Bells, Vessels, Cymbals and Gongs: Links with Prehistoric High Tin Bronzes from Mohenjodaro, Taxila, South Indian Megaliths, and Later Finds

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Introduction

The Indian ethnographic record provides a rich repertoire of traditional metal crafts, not all well documented especially from a technical perspective. During field investigations on image casting in Tamil Nadu and Kerala states in southern India first made in 1990, the author recorded lesser known, but highly skilled utilitarian crafts for making mirrors, lamps, bells, vessels and musical instruments. In 1991 the author (Srinivasan, 1997) technically documented the manufacture of high-tin beta (23% tin) bronze bowls and musical instruments and high-tin delta (33% tin) bronze mirrors in Kerala, reported in Srinivasan (1994) and Srinivasan and Glover (1995), which have few ethnographic parallels world-wide and are of significance to world archaeometallurgy. These findings are revelationary with regards to finds of high-tin bronzes from the Indian subcontinent, which may have previously been regarded as 'adventitious' or 'imported' alloys including some of the earliest reported worldwide: from the Indus valley site of Mohenjodaro (Mackay, 1938: 480–81), the Iron Age site of Taxila (Marshall, 1951: 567–69, Srinivasan and Glover: 1995) and megaliths of southern India (Paramasivan, 1941; Srinivasan, 1994; Srinivasan and Glover, 1995). In Srinivasan (1994) and Srinivasan and Glover (1995) ethnographic, literary and archaeometallurgical evidence is presented for ancient, continuing, pan-Indian and seemingly indigenous Indian high-tin bronze traditions, along with analyses of beta bronzes from some of the contexts mentioned above.

With this background, the objectives of this paper are to demonstrate that these relatively sophisticated high-tin bronze crafts are neither anomalous nor 'exotic' crafts within the local milieu, but reflect the existence of a developed copper-bronze alloying tradition in the Indian metallurgical record, which had not been previously widely recognized. Hence, these crafts are contextualized within a well articulated and mutually interactive local tradition employing a range of copper-base metals, from unalloyed copper to bell metal, and techniques such as lost wax casting, sand casting, piece-mould and closed-crucible casting, annealing, hot forging, quenching, polishing on indigenous lathes and the use of traditional furnaces. Comparisons are made with related local crafts traditions including lost wax casting of bells, lamps, large cauldrons and vessels, sand casting of cymbals, and the manufacture of beaten copper vessels, for which the author's original field observations are reported for the first time. To explore their historical significance, the linkages between these various metalworking processes and ancient finds are briefly discussed. While archaeological parallels for high-tin beta bronzes are known from the Indian subcontinent this paper reports ancient Indian parallels for the other alloys encountered in this survey such as high-tin delta bronzes and the *'vengalai'* alloy as well. The author's findings of old bronze smelting slags in Karnataka in southern India indicate unsupected local sources and manufacture of bronze which gives new depth to the understanding of the Indian bronze metallurgical tradition.

Notes on fieldwork informants and alloying trends

From an ethnographic point of view, the lost wax casting of Hindu images by *Sthapatis* (or icon makers of the status of Brahmins) from the Tanjavur region of southern India is well known (Reeves, 1962; Krishnan, 1976; Mukherjee, 1978; Srinivasan, 1996). *Madhuchehhishthavidhanam* or the lost wax process is described in ancient Silpasastras or artistic treatises such as the Gupta Manasara (ca. 3rd–5th c. A.D.) (Reeves, 1962: 29), the *Silparatna* (Von Schroeder 1981: 19), and the peninsular Chalukyan *Manasollasa* (ca. 1130 A.D.) (Reeves, 1962: 32–33).

The bustling temple town of Kumbakonam in Tanjavur district provides a thriving market for icons and metalware of a 'Hinduistic' tradition. Most ritual metal accessories were made at nearby Nacharkoil, 8 km away. Here, lost wax casting of temple bells *(koil mani)* and lamps, and sand casting of cymbals (*talam/nattuvangam*) for classical dance by the *Kammalar* (or traditional families of braziers) was observed. While the Tanjavur district is famed for traditional metalware, the temple town of Trichur in Kerala has been considered by the elite to be the source of highly prized ritual and utilitarian utensils and metalware. Hence the author visited several workshops in Kerala in 1991. The making of large beaten copper vessels by the *Chembotti*, or traditional coppersmiths, in Trichur town was noted. At Nadavarambu, Trichur district, Kerala, the lost wax casting of vessels, large cauldrons, lamps, hand bells and anklets of an exceedingly high quality using very traditional methods was documented. As for the high-tin bronze techniques the manufacture of articles of wrought and quenched high-tin beta (23%) bronze including bowls, vessels (*talavettu, olavettu, kinnam*), ladles (*shatuvam*), cymbals (*talam*) and gongs (*yaganda*) by the *Kammalar* in Payangadi, Palghat district was observed at a workshop identified by chance reported in Srinivasan (1994) and Srinivasan and Glover (1995). The manufacture of mirrors (*kannadi*) was observed (reported in Srinivasan and Glover, 1995) at Aranmula, Allepey district, of cast high-tin delta (33%) bronze which had been briefly mentioned in Mukherjee (1978). Apart from the author's independent field observations at Aranmula, some technical re-constructions on mirror making were made by the author on equipment purchased by Dr. I. Glover from mirror makers from Malakkara at an exhibition (Srinivasan and Glover: 1995). In this paper only certain aspects of these manufacturing processes are recapitulated for the purposes of comparisons with the other local metalworking traditions documented here.

Although 'bronze', 'brass', 'copper-bronze' and 'bell metal' have often been loosely used in Indian ethnographic literature, there is a need for more clarity to explore alloying trends and their function. In this paper 'bronze' is used strictly in metallurgical terms to imply an alloy of tin and copper, 'brass' as an alloy of zinc and copper. Unalloyed copper, though not very castable, is soft and very ductile and the exploitation of these properties is dealt with in the section on wrought copper work. The alloying of copper especially with lead or zinc improves fluidity for casting, while alloying with tin improves hardness. Most bronzes in general, and those found in antiquity have not much more than about 10% tin, because as-cast or ordinarily cooled bronzes with over 15% tin get increasingly embrittled due to the formation of a lower temperature eutectoid with a brittle delta intermetallic compound.

However bronzes with 20–30% tin also have useful musical, specular and reflective properties, while the addition of lead could improve castability and machinability and reduce brittleness of high-tin bronze. 'Bell metal' described the metal used to cast medieval bells (Hanson and Pell-Walpole, 1951) and usually refers to variable leaded high-tin copper alloys with up to 25% tin and up to 5–10% lead. Mirrors from Chinese antiquity usually have about 25% tin and 5% lead (Meeks 1993; T. Chase pers. comm.), while a Roman mirror analysed by Scott (1991: Plate 5) had 18% tin and 6% lead, which may also be described as bell metal.

The terms high-tin beta bronze and high-tin delta bronze used in this paper refer to unleaded, binary alloys of only copper and tin, with specific properties and proportions due to the formation of intermetallic compounds, the former with around 23% tin, and the latter with around 33% tin. While copper-tin alloys generally have limited workability, bronzes with 22–24% tin can be worked fairly extensively within 586–798° C, due to the predominant formation of a metastable plastic beta intermetallic compound (Scott, 1991: 123) of equilibrium composition of 23% tin. Furthermore the process of quenching (i.e. rapid immersion of heated metal in cooler liquid) of bronzes with around 22–24% tin within 586–798° C ensures the retention or freezing of the high-temperature beta phase as a needle-like martensite and prevents the formation of the lower temparature brittle delta component and thus improves tensile strength (Reeves et al., 1953; Rajpitak and Seeley, 1979). The presence of the needle-like beta phase in the microstructure is characteristic of quenched beta bronzes. Micro-structural study and technical investigations of a vessel from Payangadi confirmed that it was of wrought and quenched beta bronze of 22.5% tin and was consistent with the process observed by the author (Srinivasan, 1994; Srinivasan and Glover, 1995). [Analytical investigations were done using Electron Probe Micro-analysis with Wavelength Dispersive X-ray Analysis (EPMA-WDS) on a JOEL Superprobe JXA–8600.] The bowl was thus hot wrought to extreme thinness followed by quenching all in the beta temperature range, with the original ingot being 1.5 cm thick and 15 cm in diameter, whereas the final bowl was concave and of a diameter of 25 cm and rim thickness of only 1 mm. Archaeological examples from the Nilgiri and Adichanallur megaliths have rim thicknesses down to 0.2 mm (ibid.). The beta phase is essentially a high-temparature ordered intermetallic constituent, and such modern alloys for instance in the Ni-A1 system are known to exhibit superplastic behaviour (Liu et al. 1996). Apart from the attractive golden hue on polishing such vessels are used preferentially as utensils to eat from and to store edibles (Srinivasan, 1994) due to the corrosion resistance of the quenched alloy and relative non-toxicity of a high tin component due to which vessels were tinned in the past. Gongs and cymbals are also made of this alloy at Payangadi in Kerala as the quenched martensitic beta phase contributes to musical properties. For comparison this paper describes another process of cymbal manufacture by sand casting bell metal observed at Nacharkoil.

The Kerala mirrors are ingeniously made of around 33% tin bronze, consisting predominantly of pure delta phase as confirmed by micro-structural study, analytical and EPMA-WDS analysis with compositions of finished and unfinished mirrors, blank and as-cast alloy all falling within 32..4–33.5% tin (Srinivasan and Glover: 1995). The copper-tin system indicates that under usual non-equilibrium cooling conditions, within a narrow composition range of 32–34% tin the alloy consists mostly of delta phase. The delta phase is an intermetallic compound ($Cu_{31}Sn_8$) of fixed composition of 32.6% tin (Meeks, 1986: 137). Its predominance gives the alloy properties useful for mirror making as it is a very hard, silvery white compound and can take a high degree of polish free of distortions, with uniform specular reflectance across the spectrum, although it yields a very brittle alloy. Since an alloy of pure delta phase seems to have been aimed at, it is referred to here as a delta bronze. With slow cooling the espilon phase component forms rather than delta phase, while delta phase predominates only under non-equilibrium or rapid cooling conditions. Hence a thin blank of 3 mm was cast, which would cool rapidly leading to a structure with predominantly delta phase. The rapid cooling would also lead to a finer-grained, more homogenous and hence tougher structure and thus offset to some extent the disadvantage of the natural brittleness of the alloy.

Thus the paper seeks to establish that the functional properties of alloys used were well understood and exploited, although this is not perhaps well appreciated about the Indian metal tradition. This is particularly evident in Kerala, where a range of copper alloys are used for different articles within a small geographical region. In Lahiri (1995) the prominence of a 'pure' copper tradition in the Indian metal working tradition has been elegantly conceptualised. However the notions put forth in Lahiri (ibid.)—that this argument is strengthened by the lack of marked alloying traditions and the prevalence of re-cycling trends in the Indian ethnographic record—are somewhat simplistic. Undoubtedly there is a well established tradition of re-cycling of metal as seen in shops and workshops visited in Kerala and Tamil Nadu where old metalware is bartered, traded and used as scrap. However a measure of control on alloying proportions is induced by re-cycling the same type of object thought likely to be made by the same process and alloys. This is best exemplified by the wrought and quenched high-tin beta bronze workshop at Payangadi whose craftsmen mentioned that they only re-cycled vessels already made of the same process. They are well able to recognize these from the extremely thin rims, the imprints of wrought hammering, the dark, but shiny and relatively stable, patination; and indeed the author recognised stacks of such vessels on sale in Trichur. Moreover many of the crafts described here specifically use alloys made from pure metals. Mukherjee (1978) also reports this of several crafts documented by her. For instance, the artisans of Khagra in West Bengal (ibid. : 408) are said to have been "absolutely rigid about using an alloy of 7 parts copper to 2 parts tin"—which approximates to 22% tin, i.e., the composition of beta bronze.

It would be worthwhile to comment on the socioeconomic milieu of these crafts, since all the artisans complained that their lot had worsened with patronage receding to the temple towns such as Kumbakonam, Madurai, Tiruvannamalai and Trichur. The traditional vessel makers stated that they are not given any supportive 'handicraft' status and find themselves besieged by the aluminium and stainless steel industry which successfully imitates traditional designs. They added that the cost of pure metal ingots has become prohibitive, forcing them to survive by re-cycling scrap metal. Thurston and Rangachari (1909: 129) noted that although the North Malabar was celebrated for lamps and bell metal artefacts the importation of vessels from Europe had made inroads so that braziers and blacksmiths found their occupations declining. An *Achari*, making mirrors at Aranmula mentioned that with the loss of royal patronage his craft would have died out but for the interest of some western tourists visiting a nearby *ashram*. Societies such as the 'Congress of Traditional Science and Technology' are striving for greater respectability for traditional crafts, whose late founder president and eminent developmental scientist Dr. C.V. Seshadri (Sundaram, 1996) had argued that it was cost effective to upgrade or adapt technologies that rural craftsmen were already skilled at. The efforts of the Nadavarambu Bell Metal Cooperative Society are very commendable in that it has managed to preserve traditional techniques without compromising on quality while giving a fair deal to the artisans outside institutional support. However, it was interesting to note that people outside traditional castes and religious groups of artisans were also taking to icon manufacture and metalsmithing, while the participation of women in metal foundries and workshops, seen especially in Kerala, was also a significant trend.

Manufacture of temple bells, lamps and cymbals at Nacharkoil

Introduction to workshop, methods and alloys used

At a large workshop of a family of *Kammalar*, lost wax castings of large and medium sized temple bells *(koil mani)* to small hand bells *(ghanta)* were being made. The artisans said that up to 30 wt. % *velliam* (tin) was alloyed with copper to make cast bells and cymbals. SEM-EDS investigations (i.e scanning electron microscopy with energy dispersive x-ray analysis using a HITACHI S-570 with link AN-1000) of a sample of *velliam* confirmed it to be tin. However the artisan denied using *iyam* or lead, although it would be useful in reducing brittleness of the alloy for casting.

The artisans categorically said they did not use the same alloy that they used for making bells, [called *venkalai*, i.e. bell metal], for making images because they would be breakable. This indicates they were aware of the brittleness of as-cast high tin bronze alloys of over 15% tin. Moreover it is possible that since bells and vessels had uniformly thinner cross-sections compared to the surface area, it could lead to more rapid and uniform cooling of cast metal resulting in finer grain size, increased homogeneity and toughness, which may alleviate the brittleness of bell metal. On the other hand images being more three-dimensional, have thicker sections that would not cool so uniformly or quickly, which may lead to coring and segregation of one of the constituents of the alloys, with weaker grain boundaries and hence result in more embrittlement in the same alloy. In contrast, the *Sthapatis* of Swamimalai used an alloy for image casting which consisted of industrial ingots labelled "15% brass, 82% copper, 3% lead" (Srinivasan, 1996: 101). Reeves (1962: 108) observed that alloys of "75 wt. % copper, 15 wt. % brass, and 5 wt. % tin" were used at Swamimalai for making icons. (It is not clear in either case what 'brass' refers to, but it is presumed that it is an alloy of copper and zinc according to convention.) This indicates that while high tin bronze alloys were reserved for special applications, icons were cast of less brittle alloys of low-tin, leaded bronze or brass. The Kammalar at Nacharkoil also said that while *venkalai* was used for casting bells, lamps or *vilakku* were made of pittalai or brass. Brass (i.e. a copper-zinc alloy) is malleable and can hence be cold worked a lot which could be useful for casting lamps which are highly polished. The preliminary observations indicate that different alloys were selected for different objects based on their properties.

Lost wax casting of a temple bell

A large mould for lost wax casting of a temple bell (Fig. 1), or *koil mani*, was under preparation about 80 cm long with a diameter of about 50 cm at the rim. First an inner clay core was built on a horizontal axle and finely moulded into a bell shape using a hand-turned lathe arrangement. The horizontal wooden axle tapered at both ends and was placed within a trench about 1 m long and 30 cm wide and deep. The axle had wheels at the ends embedded in grooves to keep the axle in place. The mould was made around the axle leaving a few centimetres clear at the edge, so that the finished mould could be lifted out of the trench. This contraption was set up in an open yard so that the mould could dry out in the sunshine.

The inner clay core was first built along the axle in three layers from coarse, medium to fine. The innermost coarse core layer was made by packing river loam from the Kaveri river to get a sturdy, yet porous, core. The hand-turned lathe arrangement was as follows: The *Kammalan* pressed a steel spatula against the clay put on the axle for the mould by holding it out with the right hand on a long piece of wood, while another piece of wood was placed perpendicularly across this piece of wood and held under his foot so that the spatula was held in place. Then the axle with the clay could be turned

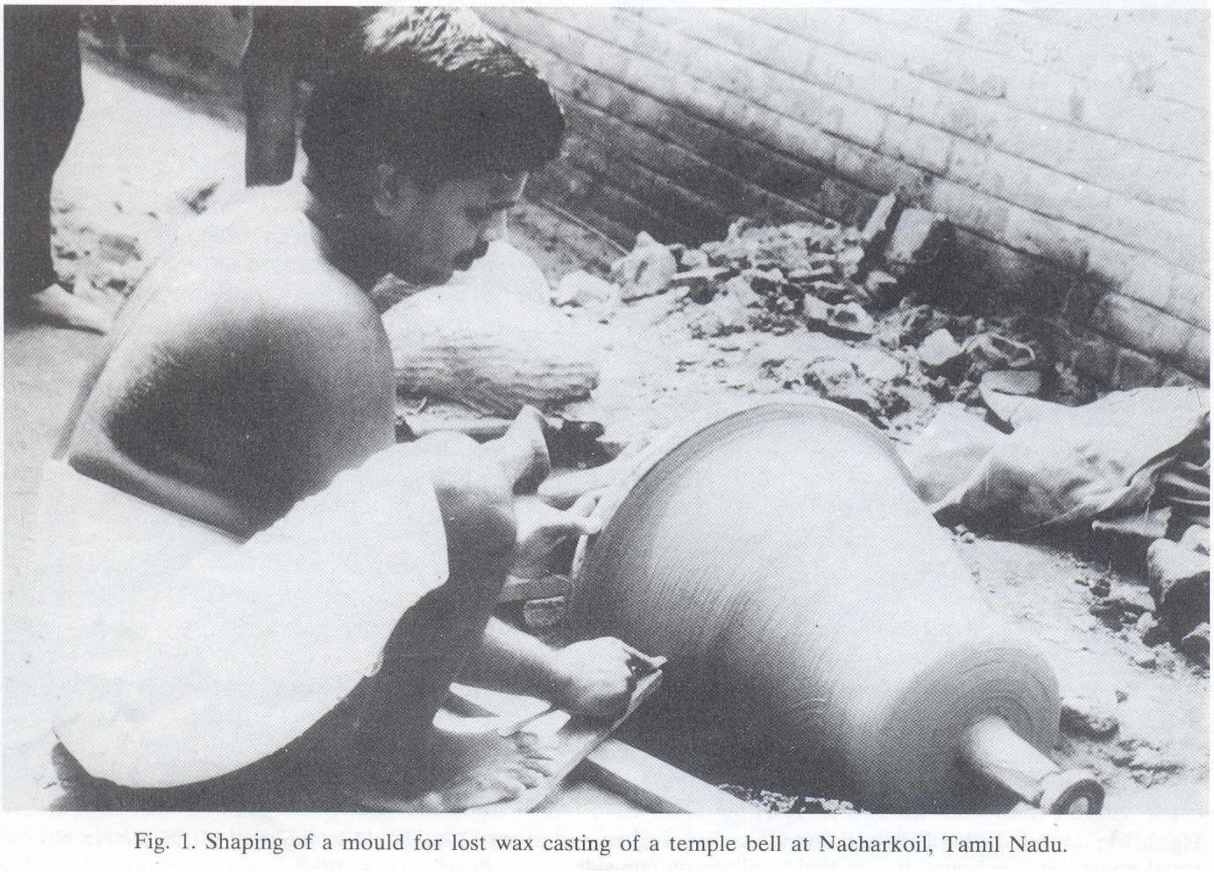

Fig. 1. Shaping of a mould for lost wax casting of a temple bell at Nacharkoil, Tamil Nadu.

with the left hand to shape the clay into the mould (Fig. 1). The coarse layer formed the bulk of the core, taking up three fourths the radius of the flaring rim. Then the next clay layer mixed with brick dust was similarly applied to a thickness of a fourth of the radius of coarse clay. Then a final layer was coated as a fine slurry of clay finely sieved to remove coarse inclusions, mixed with a dried cowdung paste. The fine layer was turned against the spatula and the bell shape created by pushing the spatula gradually forward and sideways from the edge of the flared rim to the apex of the bell. The mould thus created had a perfectly symmetrical shape and quite a flawless surface required for a smooth finish for the casting.

Then strips of wax were held against the mould and the spatula heated over a brazier and held against the wax so that it got turned over the mould and this was repeated until a wax layer of the shape and requisite thickness of bell had been skilfully applied. The surface of wax was smoothed by turning against the spatula and then invested or covered with the three layers of clay. A sprue (for pouring metal) and a vent (provided for the escape of gases in the mould) were left exposed around the convergent portion of the bell-shaped mould (Fig. 2). The mould was left to bake in the sharp sunshine for some days for thorough drying as moisture could release gases during pouring, causing sudden expansion and bursting.

The next process was de-waxing, i.e., ridding the wax from the mould by melting it out. This was done *in situ* by lifting up the mould by the ends of the horizontal wooden axle, putting heated coals in the trench and then replacing the mould. Wax melts at about 100°C, but the mould was heated beyond that temperature to rid it of moisture. In the process the mould would have been pre-heated, i.e. heated prior to casting of molten metal. The mould was covered up with cowdung cake fuel to ensure

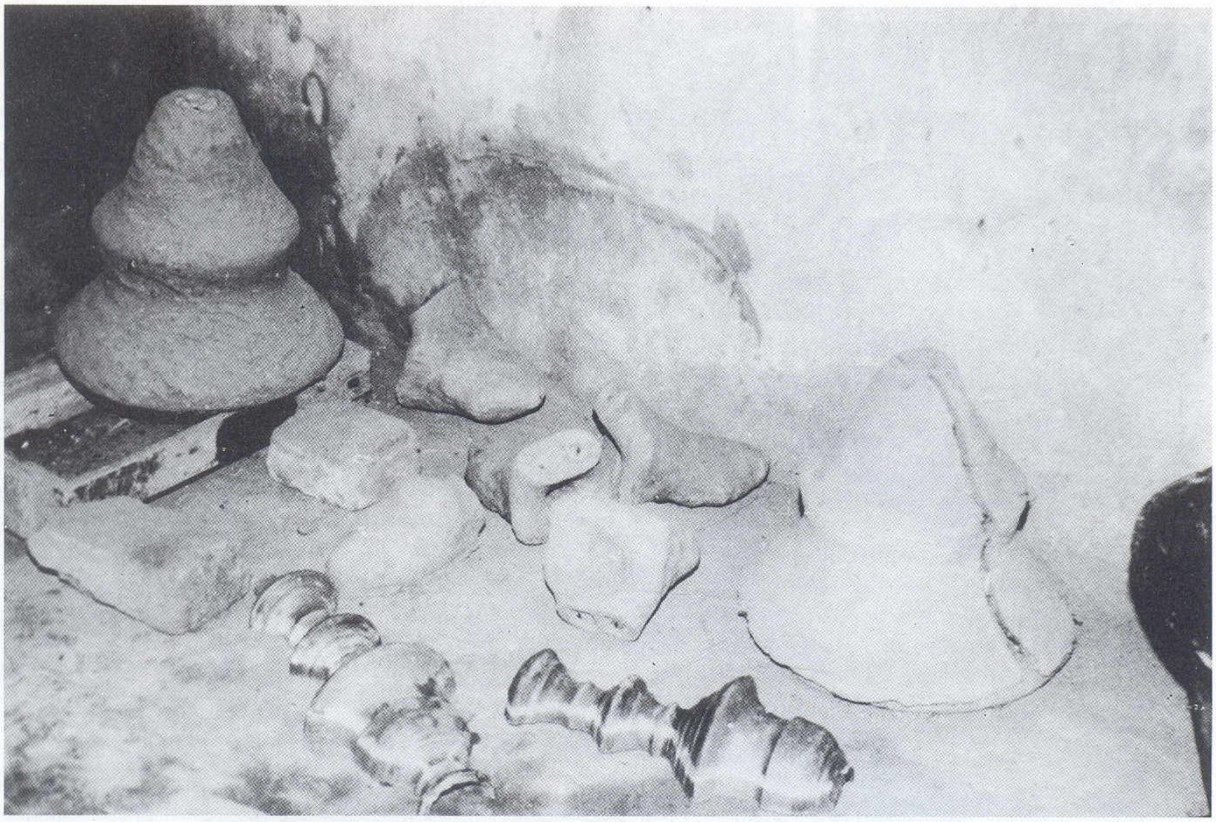

Fig. 2. Moulds for casting bells and lamps showing a sprue and a vent. The mould to the right of the picture has had metal poured in it indicated by the slight spillage on one side.

uniform heating of the mould, and occasionally turned so that the melted wax was collected from the runners at its convergent end.

After dewaxing, the mould was lifted out of the trench by the ends of the axle and carried into a covered shed. Here a large crucible was fitted within a trench 30 × 30 × 60 cm and heated by a blower, buried underground. A wall 60 cm high × 1.5 m long separated the person operating the blower from the crucible to reduce health hazards while making it possible to note when the alloy was molten and hence avoid super-heating, i.e., heating the mould much above the melting/solidification point of metal which could burst the mould during pouring due to the sudden expansion of the mould from the excess heat. The bell-shaped mould was propped upright with the end of the axle wedged into the mud floor and molten metal was poured from the sprue at the top of the mould (Fig. 2). The cast bell was retrieved after cooling by breaking open the mould. In this workshop final polishing is now done using electric lathes and polishing burrs.

Sand casting of cymbals at Nacharkoil

Also noted at Nacharkoil was the sand casting of cymbals *(talam, nattuvangam)* for classical dance and music. Whereas castings requiring three dimensional accuracy were made using lost wax techniques, the cymbals were relatively thin, of simple concave relief, making it possible to use the quicker method of sand casting. This involved the making of a two-piece sand mould of which the bottom piece would be referred to in metallurgical terms as the 'drag' and the top piece the 'cope' consisting of a vertical pouring channel or runner (after Higgins, 1974: 65–66). Each consisted of moulding sand in a box-like frame: with the mould cavity formed after sandwiching a pattern between the cope and drag. Here the pattern was a set of pre-cast cymbals of which the original pair could have been made of wrought and quenched beta bronze as observed at Payangadi and discussed further. The drag consisted of the concave side of the pattern formed by the cymbals and the cope the convex side (Fig. 3). Alluvial silt from the Kaveri river was used, sieved well to a consistent grain size, not coarse but not too fine. The sieving also ensured that the moulding sand was a bit porous so that the gases could escape out during casting which could otherwise cause porosity defects. The moulding sand could be described as 'green sand', i.e. sand with some clay and moisture content to act as a binder (after Heine et al., 1976: 84–89). To make the drag with a pattern of the concave side of the cymbals, a hollow rectangular wooden frame of about 50 × 30 cm was placed against a flat wooden board and the two cymbals were placed concave faces down on the board. Sand was sprinkled using a sieve until the cymbals were completely and substantially covered. Then sand was scooped into the frame and filled up to the rim and compacted by ramming with a wooden mallet, but not so tightly as to prevent the escape of gases when pouring metal. The excess sand over the rim was levelled with a wooden board. This was placed on top and the frame inverted holding top and bottom boards. Thus the cymbals were now on top. A shallow horizontal gate was made connecting the two cymbals which were gently prized out to leave a perfect pattern for the concave face of the cymbals.

The pattern of the cope with the convex face of the cymbals was made in two steps. The first step involved the same process described above of making the drag with a pattern of the concave face, except that the cymbals were not prized out of the pattern. In the second step another wooden frame intended for the cope was placed over this mould with the cymbals being concave face up and packed with sand, and then both the frames were inverted so that the bottom frame now had a pattern for the convex surface forming the cope. To prevent the surfaces of the two moulds from sticking together, a whitish more siliceous sand had been sprinkled over a fully dried surface skin. A wooden rod had been placed upright in the frame intended for the cope between the two cymbals during ramming of sand. After inverting the frames the top frame with the concave pattern was removed. The bottom frame was thus the cope with the cymbals lying convex face up, over a pattern of convex shape. The cymbals were then carefully removed to give the convex pattern of the cymbals. The wooden rod was pulled out to leave a hollow runner (i.e. pouring channel) in the cope.

The frames for cope and drag had wooden pins over the edge to rivet one on the other. Finally, for casting the metal the cope with the convex pattern was rivetted above the drag with concave pattern.

Fig. 3. Investing a wax model for a lamp with the finest grade of clay at Nadavarambu; wooden wheels for moulds for *uralis* or cauldrons seen in background.

Metal flowed down the vertical runner in the cope into the horizontal gate in the drag and into the cavity for the cymbals. After the metal had cooled the cope was lifted off the drag and overturned along with the cast metal cymbals. These were pulled out of the cope and the runners cut off. The sand mould, which is not heated, results in more rapid cooling than an investment casting, while the thin cross-section of the cymbal would also contribute to fairly rapid cooling (Higgins, 1974: 70). This may contribute to a tougher casting due to a finer grain structure, countering the brittleness contributed by the high tin content of bell metal.

Lost wax casting of *uralis*, bells and lamps at the Nadavarambu Bell Metal Society

At the huge workshop of the Nadavarambu Bell Metal Society, lost wax casting was undertaken of a range of metalware such as large cauldrons for feasts called *urali* of 1 m diameter, smaller shallow vessels of 40 cm diameter, a range of lamps or *vilakku*, hand bells, incense burners and heavy anklets. The process of making moulds for vessels of about 40 cm diameter, 10 cm high and 1 cm thick was observed. An inner vessel-shaped refractory layer was covered by a wax infill with an outer refractory layer applied over it. The inner portion was made by moulding clay into a circular shape with a raised edge. The centre of the mould had a raised portion with a hole for fitting the mould on to the lathe, which would eventually form the runner. The moulding material was applied as three layers. The first layer consisted of coarse clay from the river mixed with shredded jute cloth. Apart from acting as a binder for the clay, the shredded jute cloth would result in a more porous, ventilated mould as it would burn away when the mould was heated and thus facilitate gases to escape during pouring of metal which could otherwise result in a spongy, porous casting. Moreover a porous mould would be better able to withstand thermal shock (i.e. cracking of the mould due to heat from the molten metal) by enabling the release of stresses around the porosities. The *Manasollasa* (Reeves, 1962: 32–33) also mentions that the investment over the wax model should be made of clay 'mixed with cotton fibre shredded a hundred times' which could have served a similar technical purpose to the shredded jute fibre.

After roughly shaping the mould from the coarse layer, it was mounted on a hand-turned lathe. The axle of the lathe was fitted on a wooden frame over a trench such that the rod was passed through the central hole in the mould. To one end of the axle was fitted a cylinder of resin with circular grooves cut into it, which was used to get a grip when turning the mould. Then a person pressed a spatula against the surface of the mould while the other hand rotated the resin cylinder thereby turning the mould. Then a second mould layer was applied of a fine black alluvial clay. Finally on the surface to be next to the wax, a third layer of wet, fine, sieved mud mixed with dried cow dung paste and lamp black was applied. A final smooth finish was given by holding fine dry powder of this mud against the mould and rotating the resin cylinder. Figure 3 shows the finest grade of clay being applied on wax models of lamp bases.

The admixtures are not functionally irrelevant even in terms of modern investment casting. Dried cowdung paste is a good binder of fine mesh. Furthermore it would contribute to a fine charred layer after the de-waxing and pre-heating of the mould which would be adsorbent (which refers to the process of gases being drawn into a carbon-rich surface layer) and maintain an internally reducing environment (i.e. carbon-rich rather than oxygen-rich). The carbonaceous, sticky lamp black would similarly serve to minimise formation of gases by oxidation which could lead to porosity defects. The *Silparatna* (Von Schroeder 1981: 19) and *Manasara* (Reeves 1962: 29) prescribe that clay of the finest grade be applied next to the wax model mixed of finely pounded cowdung, which thus makes sound technical sense.

Large eye-catching moulds were being made for the cauldrons or *uralis,* mounted over a pair of wooden wheels 1 m in diameter with wooden spokes, fitted on to two ends of an axle (Fig. 7). The wood had already been carved to the shape of the *urali.* The inner mould was made over the wooden wheel in three layers as described above. Then a wax layer was applied of the thickness of the vessel of up to 5 cm for the large *urali.* This wax was a mixture of paraffin wax, beeswax and castor oil and was applied with a heated spatula. The wax was smoothly finished by pressing the spatula against it as the mould was turned on the wheel. Finally the wax model was invested with the three layers of clay. The dried mould was prized off the wheel, re-inforced with large pottery tiles and dried on a large mound of sand to drain it of residual moisture. The moulds had at least one sprue and vent.

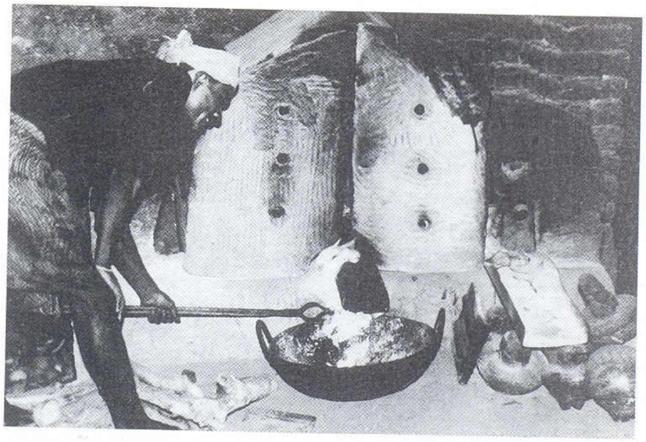

Fig. 4. Traditional furnace at Nadavarambu for dewaxing, pre-heating mould and melting metal to be cast, with channel for collecting melted wax to one side.

An ingenious traditional furnace (Fig. 4) was used to expel wax inside the mould and then pre-heat the mould to the same temperature as the molten metal to be cast. This would prevent sudden expansion and bursting caused by a significant difference in temperature between mould and molten metal. Pre-heating is essential for fine details in casting as the metal remains fluid longer (Smith 1982: 136).

Thus the arrangement consisted of two traditional furnaces about 2 m long × 1 m wide, × 2 m high with sloping roofs with a chimney and perforated doors which could be slid open (Fig. 4). The mould to be dewaxed was placed inside the furnace with its orifice aligned with a gap along the breadth of the furnace which sloped into the ground to recover the melted wax. The fuel and fire was

Fig. 5. Lamp being polished at Nadavarambu by affixing it on rope-turned lathe.

stoked on the other side using traditional goat skin or leather bellows. The mould was placed in the furnace almost at the same time as the crucible with the metal to be melted. After the wax had run out of the mould it was left in the furnace until the metal in the crucible was molten so that mould and molten metal would be at roughly the same temperature. Wax melts at about 100–150° C, while the mould would turn red hot around 600–700° C. Copper has the highest melting point over tin, lead or zinc of 1083° C, so that the furnace was probably heated up to this temperature. The closed atmosphere would ensure reducing conditions to suppress the melting point and prevent oxidation of metal. The craftsmen could peer through the perforations to see when the metal was molten and red hot.

For pouring, the heated, dewaxed moulds were removed from the furnace and immediately packed at an incline in a mud trench to reduce spillage hazards if the mould burst. While pouring a burning ring of cloth was held at the mouth of the sprue so that locally reducing conditions were maintained to avoid an oxidised fire skin. The *Manasollasa* (Reeves 1962: 32–33) also recommends the use a lighted wick near the mouth of the mould which is thus practical.

Tall lamps, or *kutuvilakku*, were made by casting in two to three different pieces with grooves made in the wax model so that the castings could be fitted, one piece into another. Finishing and polishing of cast lamps and vessels was done using traditional rope-turned lathes (Fig. 5). The contraption consisted of a long iron axle protruding about 1 m, set inside a brick wall for re-inforcement slightly above floor level. Its first 50 cm near the wall was surmounted by a cylinder of dammar resin supported by a wooden frame. Rope was wound around this resin cylinder for grip and turned by one man. A second cylinder of resin of 30 cm was attached to this on the axle. For polishing, the lamp base was heated over a pit of charcoal to about 150° C and pressed against this second resin cylinder softening it. Once the resin cooled it hardened and set, adhering the lamp section to itself horizontally. For polishing, a man pressed a steel spatula and corundum powder against the lamp while it was turned by the other man who pulled ropes wound on the resin cylinder. The lamp section could also be propped inside a loop of rope hung from the ceiling. Minor defects were sealed with lead or *iyam.*

Beaten copper work at Trichur

At the workshops of the *Chembotti* or coppersmiths (*chembu/cheppu:* copper in Tamil and Malayalam) in Trichur large storage vessels for grain up to 1 m in diameter and 50 cm high are made of beaten copper.

Copper can be drawn to 90% by cold deformation (i.e. working or hammering at room temparatures) before annealing is required (West, 1982: 174). Metal becomes increasingly hard and brittle or breakable with deformation caused by working, and annealing refers to the prolonged heating of metal to restore its malleability, to soften it, or to reduce stresses and strains built up due to working. While copper can be hot worked between 750 and 950° C, a softening annealing can be done between 200 and 650° C, and stress relief annealing between 150 and 200° C (ibid.: 162). Some parts of the vessels were made essentially by cold deformation with occasional softening or stress relief annealing. At the outset a cylindrical billet of cast copper of about 20 cm length and diameter of 10 cm was used. From these circular sheets of diameters of about 80 cm could be hammered out. Tough pitch copper (i.e. as-cast copper which has some oxygen impurities) solidifies with a flat surface (ibid.: 167) and the process of hammering of a circular base or lid of vessels used this typical morphology. An upright cylindrical iron anvil of a height of 80 cm, and a diameter of about 6 cm was used for hammering by a man who sat on a stool beside it. The flat end of the cast cylindrical copper billet was placed against the anvil and the top end hammered. By doing so the metal was extruded at the bottom end touching the anvil along a plane perpendicular to the vertical blows, in circular shape. The extruded plane could then be hammered out and extended by turning it after each blow resulting in a trademark pattern of spiral punchmarks. The copper billet was thus alternately hammered from the top end and then the horizontal extruded plane hammered out. One of the artisans had cut the extruded plane into a cross shape and would then continue to hammer down the knob of the billet, as described above, till it was reduced to a sheet. Thus the protruding parts of the cross-shaped sheet could be folded up and joined at the seams to get a rectangular-based vessel.

Copper sheets were also shaped to form raised cylindrical sides of the large vessels of 50 cm high: by using the upright anvil as a diameter and hammering and turning the sheet against it. In other operations a large pre-cast vessel, of harder bronze, was used as the anvil to cold hammer and shape the copper sheets on. Occasionally the hammered sheets were given a softening anneal to make them more malleable. Finally the flat circular base was peened on to the base of the raised cylindrical rim to give a finished vessel. The finished vessel was held by long iron poles, over 1 m long, and mildly heated on a bed of heated charcoal probably as a stress relief anneal at around 150° C to improve durability of the finished product.

Vessels of cast bell metal were given a cladding by hot hammering sheets of copper (annealed to around 750°C) on to the harder bell metal. Such vessels were attractive as well as practical with a golden-hued, relatively non-toxic tin-rich interior, while the rich copper-hued exterior had a pattern of circular or spiral punch marks.

Comparisons between the various metalworking techniques

The ethnographic survey undertaken in Tamil Nadu and Kerala and ongoing technical observations indicate adept manufacturing techniques using traditional materials. The casting processes described, especially the lost wax process at Nadavarambu in Kerala, can be seen to be faithful to ancient Sastraic textual prescriptions, such as those found in the *Manasollasa, Manasara and Silparatna*, with fairly sound practical and scientific basis: serving to create a ventilated, yet resilient mould while maintaining a reducing environment for efficient casting. The traditional lost wax casting furnace used at Nadavarambu is an interesting innovation serving to dewax the mould as well as to heat the mould and the molten metal in the crucible to the same temperature before casting. The choice of casting procedures can be seen to be based on functional requirements. For instance the sand casting process for cymbals at Nacharkoil departs from the usual lost wax casting process for bells and lamps at Nacharkoil in Tamil Nadu and at Nadavarambu in Kerala. Although the antiquity of the sand casting process in the Indian context is not known, the materials used at any rate at Nacharkoil are traditional. The sand casting process is believed to have been used in Europe by the medieval period.

The comparative survey indicates that the high-tin bronze crafts from Kerala of cast delta bronze mirrors (Fig. 6) and of wrought and quenched beta bronze vessels (Fig. 7) are not isolated developments but are consistent with proximal craft traditions such as, quite obviously, bell metal casting, and wrought and annealed copper work. The idea behind water quenching of very thin cross-sections (<1 mm) of high-tin beta (23% tin) bronze; the casting of a thin blank (3 mm) of delta high-tin (33% tin) bronze to promote formation by rapid cooling of the desired delta phase which is a non-equilibrium structure; and the sand casting of fairly thin (about 1 cm thick) bell metal cymbals leading to quicker cooling than the lost wax process; may all stem from the perceived usefulness of rapid cooling processes in obtaining optimal properties from high-tin bronzes for certain applications, while also reducing brittleness of bronze of a high tin content.

The casting of high-tin delta bronze mirror blanks observed in Aranmula, Kerala may be compared with the other casting processes. To cast the mirror blank no more than 3 mm thick, a specifically designed two-piece mould was used (Fig. 6), kept apart by spacers of 3 mm thick of the same alloy, bound with iron wire and encased in

Fig. 6. Section of crucible-cum-mould from Malakkara showing cup to be filled with mirror alloy (of high-tin delta bronze) and the two-piece mould of pre-fired clay discs with slipped surfaces.

Fig. 7. High-tin beta bronze ingot (with 22.5% tin) being forged into a concave shape at Payangadi by hammering with the *cherangulam* when it is in plastic beta phase temperature region.

clay with an attached closed crucible (Srinivasan and Glover: 1995). The two-piece mould consisted of pre-fired clay discs with a fine slip that had been poured on flat on each inner face and fired grey under reducing conditions, to get the most flawless and adsorbent surface for casting the blank. The lost wax processes also essentially employ a pre-fired mould with a slip-like layer of the finest grade of clay adjacent to the metal to be cast. The metal for the Kerala mirrors was melted in a sealed crucible cavity in the neck of the jug-shaped crucible-cum-mould (Fig. 6), which was connected to the two-piece mould by a hollow channel, and then the neck was tipped over so that the metal flowed into the space for the blank within the two-piece mould. This closed-crucible casting of a mirror blank in Kerala has a parallel in the eastern Indian *dhokra* bronze casting process (described in Reeves, 1962: 48), while the *Manasollasa* (ibid. 32–33) also mentions the melting of metal in closed crucibles. The closed crucible would minimise oxidation losses and surface defects due to microporosities caused in tin bronzes

Fig. 8. View of several wrought high-tin beta bronze bowls which have been quenched giving a sooty skin with spiral punch marks from hammering. The quenched bowls in the picture are about to be polished and finished.

by dispersed shrinkage and formation of gases from dissolved hydrogen (Heine et al., 1976: 347–348).

A specialised facet of the various processes is the polishing of metal, moulds and models. In the lost wax casting processes at Nadavarambu a remarkable lathe-turned finish is achieved on cast metal using specially designed rope-turned hand lathes using grips made of resin and polishing with powders including corundum. The effective use of hand-turned lathes is made both at Nacharkoil in Tamil Nadu and at Nadavarambu in Kerala in getting well finished moulds and wax models with curvature for bells and vessels. In the making of the high-tin delta bronze mirrors the polishing stage is critical to obtaining the mirror finish. This is done by mounting the cast oval mirror blank (3 mm thick and 7 cm long) in a wooden polishing board, by embedding it in resin thus re-inforcing the brittle alloy, and lapping it against a wooden plank with hessian cloth with different grades of polishing powders as described in Srinivasan and Glover (1995). The final polishing powder is of the brittle and hard powdered mirror alloy which ensures that the same alloy is smeared into defect for the best reflectance. At Payangadi in Kerala the wrought and quenched high-tin beta bronze bowls or gongs are given a spectacular golden polish seen in a finished bowl (Fig. 8) by using scrapers alone without polishing powders and by using a hand-turned lathe arrangement with a wooden board on which the object is rivetted as seen in photographs published in Srinivasan (1994).

Vessels were made at Payangadi by casting a flat circular ingot of beta bronze with around 23% tin, heating or annealing it in the beta temperature range around 600–700° C and hot hammering in this temparature range (Fig. 7), with the cycles of annealing and hammering being continued for about 4 hours until a concave bowl was obtained, followed by quenching at around 600° C leading to a typical alpha plus beta phase microstructure (ibid.). The spiral pattern of punch marks of hammer marks seen typically in the wrought and annealed or beaten copper work seen at Trichur is also manifest in the wrought and quenched beta bronze process observed at Payanagadi, especially on the unpolished and as-quenched bowls (Fig 8). Both reflect a process of hammering out the ingots spirally outwards from the centre. Although the overall deformation achieved in the wrought copper process is much greater, the rim thinness achieved in the wrought and quenched beta bronze process down to even 0.2 mm, seems singular which may be due to special factors of the plasticity, and tensile strength of the beta phase. The possible superplastic nature of this material is currently under investigation by the author.

Thus a certain common knowledge seems to be shared between craft groups of the properties of alloys, waxes, resins, the use of rope-turned lathes for polishing and decorating, refractory materials for lost wax moulds, sand casting, piece-mould casting and slip casting, and such like.

Antiquity of the processes

Parallels are found in Indian antiquity for most of the processes described above. In the Meenakshi Temple Art Galley, located inside the complex of the temple to Goddess Meenakshi in Madurai, Tamil Nadu the author noted a large *urali,* or cauldron very similar to the ones made at the Nadavarambu Bell Metal Society, with a dark stable patination suggesting some antiquity, while the display was attributed to the 11th–12th century along with some associated Pandyan style statuary bronzes. Kerala has been renowned for its beaten copper work which covered the tiered and conical roofs of its wooden temples, while Lahiri (1995) reports the repute of the *Chembottis* of the Malabar in 19th–20th European century accounts. The large temple bell being made at Nacharkoil recalls that of the temple bell within the main entrance portal of the *vimana* of the 10th–11th century Brihadisvara temple of Rajaraja Chola at Tanjavur, which may well be the original from the state of corrosion. The curvature of such bells and that of several ancient Indian vessel types can be explained if the clay moulds were turned on lathes. The Chola bronze Nataraja or Dancing Siva from Melaperumbalam in Government Museum, Madras (acc, no. 40/36) depicts a dwarf or *gana* playing hand cymbals similar to contemporary ones. Tamil inscriptions of Rajaraja Chola often refer to *segandigai* or gongs for playing music (e.g. Srinivasa Rao 1952: 220). This may relate to the Malayalam word *yaganda* used to describe high-tin beta bronze gongs at Payangadi.

Coming to the evidence from analyses of artefacts, the alloy *'vengalai'* said to be used by the Nacharkoil artisans of 30% tin bronze with no lead, does have an archaeological parallel in a binary tin-bronze vessel from the Nilgiri megaliths with 30% tin Breeks (1873: 63, 156). Six 11th-century temple bells from Kulpauk village, Warangal district of Andhra Pradesh of the Kakatiya period were found to consistently have about 17% tin and 12% lead (Rao et al., 1981: 27–35) which may be described as bell metal.

There are also some highly intriguing analyses on high-tin bronzes from the Indus Valley site of Mohenjo-daro (Mackay, 1938: 480–481) reported to come from corroded samples from deep digging in Block 7 of the DK area. Sample DK 9722 found at 30 feet below datum has 22.2% tin and 0.86% lead, i.e. matching the composition of binary beta bronze, sample DK 9442 from 24 feet below datum has 22.1% tin and 14.9% lead, being a leaded beta bronze or a bell metal, while sample DK 9567 has 26.9% tin found at 26.8 feet below datum. These suggest an experimental phase in the use of high-tin bronzes and indeed beta bronzes at Mohenjo-daro, while Mackay's notes suggest that he did not doubt that these were from an Indus valley context (ca. 2000 B.C.).

As for the Kerala high-tin delta bronze mirrors (Fig. 9), very interestingly, the analysis of a sample from Sonepur Pd II from the Historical Period in Eastern India is reported to be bronze with 32.42% tin (Biswas 1996: 187). (The Historical period generally refers to the period from ca. 500 B.C. to the early Christian era). This is hugely significant because its composition closely matches that of high-tin delta bronze, suggesting that the specialised alloy for the Kerala mirror was indeed used anciently in the Indian subcontinent. A mirror from Taxila is reported to be of 25% binary tin-bronze (Marshall, 1951: 567–569) and is thin and flat recalling to the shape of the Kerala mirror blanks. Mirrors are also reported from Quetta and Harappa from Indus Valley context (ca. 1900 B.C.) of flat circular shapes (Association Francaise d' Action Artistique Paris 1988: Fig. 159, 160, 161) which could have been cast

Fig. 9. High-tin delta bronze mirror made at Aramula, Kerala.

in narrowly spaced two-piece moulds similar to the Kerala mirrors. The use of the wooden polishing board itself as the mirror after polishing the blank is postulated in Srinivasan and Glover (1995) from iconographic comparisons of medieval sculpture. Mirrors are also reported in the Nilgiri megaliths along with the high-tin bronze bowls in Breeks collection at British Museum.

In Srinivasan (1994) and Srinivasan and Glover (1995) analyses and some micro-structural investigations made by the author are reported of samples of high-tin beta bronzes (22–24% tin) including vessels from the Nilgiri megaliths, ca. 500 B.C. (acc. nos. 807, 806) and Adichanallur burials, ca. 800 B.C. (acc. no. 61, 69) of South India from Government Museum, Madras, from the Gandharan Grave Culture of Taxila (ca. 1000 B.C.), coins from the Andhra Vishnukundin period (ca. 4th century B.C.) and vessels from the medieval Chola period (ca. 10th–12th century A.D.). [It may be noted that in Srinivasan (1994) the captions for the microstructures figs. 59.5b and 59.5d are accidentally interchanged]. The microstructures (ibid.) suggest extensive plastic deformation in the Nilgiri and Adichanallur bowls down to 0.2 mm indicated by the extensive needle-like beta phase matrix being interspersed with alpha phase with annealing twins, and the complete absence of as-cast dendritic patterns in the alpha phase. On this score the plastic deformation indicated by the microstructures of comparable high-tin bronze bowls from Ban Don Ton Ta Phet, Thailand, ca 4th century B.C. (Rajpatik, 1983; Rajpatik and Seeley, 1979) seems lesser with many showing remnant as-cast dendritic patterns, while Goodway and Conklin (1987) describe more limited working in the contemporary making of gongs in the Philippines.

Although non-Indian sources had formerly been attributed to the bowls from the Nilgiri megaliths with reason (Leshnik, 1974; Rajpitak and Seeley, 1979) they closely resemble the wrought and quenched high-tin beta bronze bowls from Payangadi, both stylistically and metallurgically, so that it now seems likeliest that they were made in ancient Kerala which is also consistent with local history (Srinivasan 1994). Indeed Allchin and Allchin (1982) have postulated indigenous developments concerning the south Indian megaliths. More archaeology in the Kerala and Malabar region, which is sadly rather neglected, would help to throw further light on its ancient metal industry. Rather like the lost wax casting tradition, the wrought and quenched high-tin beta bronze process at Payangadi, Kerala represents one of the oldest known surviving metallurgical traditions in the Indian subcontinent.

The sources of tin, a scarce commodity in India today, has posed the engima in attributing Indian sources to these objects. However Malroney (1975: 36) mentions that tin was one of the items sent out of the Karnataka coast in Solomon's times (i.e. pre-Christian era) with ivory and apes'. Kuppuram (1986: 89) mentions a 11th century A.D. reference from the domain of the Imperial Cholas of Karnataka (with their capital at Talakkad in Hassan district of Karnataka) to the collection of a fee on exported goods such as tin and lead, along with other local items such as rice, sarees, cotton-thread, gold, rock-salt, areca, and sandal. Interestingly investigations by the author on slags from the ancient mining region of Kalyadi within Hassan district of Karnataka indicate that these are bronze smelting slags from co-smelting copper and tin ores, rather than casting slags from alloying copper and tin (Srinivasan: in press). This is indicated by prills with a uniform composition of 7% tin bronze (analysed by EPMA) and globules of metallic iron, which would only be formed under highly reducing and high temperature smelting conditions. Since trade in tin is more likely to have been in tin ingots than in ore, this strengthens the evidence for indigenous ore sources of tin that could have been exploited in South Indian antiquity to make such artefacts.

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