# Skilled mirror craft of intermetallic delta high-tin bronze ($Cu_{31}Sn_8$, 32.6% tin) from Aranmula, Kerala

*Sharada Srinivasan* and Ian Glover*

*In the village of Aranmula, Kerala, an extraordinary metal mirror is traditionally made of delta high-tin bronze, i.e. a binary copper–tin alloy of high tin content consisting almost entirely of the delta phase (δ), which is an intermetallic compound ($Cu_{31}Sn_8$) of composition 32.6% tin. This is an ideal alloy to polish into a mirror due to the silvery colour and high hardness. The presence of this delta phase is optimized, and its high brittleness offset by a clever casting and polishing process. This article puts together new insights based on the authors' field and technical investigations on how this mirror is skillfully made using low-technology, organic and everyday materials to get a sophisticated high-technology end-product.*

**Keywords:** Craft, delta high-tin bronze, intermetallic compound, mirror.

MIRRORS had both aesthetic value and magico-religious significance in parts of Asia, as in China and India. Bronze mirrors with figurines on handles are known from ancient Egypt. Flat, circular tanged mirrors were found from Harappan contexts northwest of the Indian subcontinent at Quetta and Harappa in Pakistan (ca. 2000 BC) and Dholavira in Gujarat, India. These would probably have been made of bronze of low tin content (i.e. <10% tin).

Towards the centuries before and after the common era, bronze mirrors of higher tin content came into vogue in various parts of the ancient world. Whereas lower tin bronze consisting predominantly of the coppery-coloured alpha solid solution (<15% tin) has poorer reflectivity, as-cast higher tin bronze has much higher reflectivity due to the increasing presence of an alpha-plus-delta eutectoid phase. This is a solid mixture of the alpha phase and the 'delta' component of bronze, which is a silvery white intermetallic compound. Since this delta component is also highly embrittling, as-cast higher tin bronze mirrors usually had lead alloyed to lower brittleness. This is because lead would fill inter-dendritic spaces, being a greasy material which is not soluble in copper. Such examples of cast bronze mirrors with 20–25% tin and 5–10% lead are widely found from Han China and the Roman world from the Christian era[1]. Bronze mirrors are amongst the most prolific and artistic of Chinese objets d'art. However, while the addition of lead improves castability, it might have compromised the reflectivity, since lead is an opaque material, immiscible in copper.

A unique mirror-making tradition survives at the village of Aranmula, Kerala, southern India. Here, a cast high-tin bronze mirror of 33% tin with highly specular or reflective properties is made which is comparable to, if not better than, modern mercury glass-coated mirrors. The presence of the brittle silvery-white delta phase of bronze is optimized while avoiding the use of lead, which could have dulled the mirror effect. General or anthrolopogical studies have been made on the metal mirror craft at Aranmula[2]. S.S. documented the making of metal mirrors from Aranmula in 1991, followed by detailed technical and microstructural studies on equipment purchased in early 1992 by I.G. from mirror-makers hailing from Malakkara, close to Aranmula[3–5]. These comprehensive metallurgical investigations on mirror alloys and a finished mirror first established that the Aranmula mirrors were uniquely made of what we describe as a high-tin 'delta' bronze, i.e. a binary copper–tin alloy with 32–34% tin, closely matching the composition of the pure delta phase of bronze, an intermetallic compound ($Cu_{31}Sn_8$) of fixed composition of 32.6% tin. As the delta phase is a hard and silvery compound, this composition yields ideal properties for a mirror as the alloy can be polished with the best possible uniform reflectance across the spectrum. Moreover, the delta phase, being a stable compound, does not corrode or tarnish easily. This article reports previously unpublished details on the manufacturing processes of the delta high-tin bronzes based on further field investigations which the authors undertook again in 1998 at Aranmula. It explains how the delta high-tin bronze com-

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position was skillfully isolated or optimized and polished to yield the best possible mirror effect. This article also suggests that this high-tin bronze mirror craft probably evolved out of longstanding Indian traditions of unleaded high-tin bronze usage with a couple of mirror specimens with 25–30% tin, going back at least to Iron Age sites such as Taxila and the Nilgiri cairns.

## Optimizing intermetallic delta compound: Metallographic details of mirror

The entire Aranmula mirror-manufacturing process seems to be geared at optimizing the presence of the delta phase, which the copper–tin phase diagram indicates forms only within a narrow composition range of bronze of 32–34% tin at non-equilibrium conditions. This silvery alloy shatters quite easily, akin to brittle fracture in glass, as observed by the authors with a thin cast blank. However, in the Aranmula mirror process, this brittleness is offset not by adding lead but by casting a thin blank, no more than 3 mm thick, which would thus cool more evenly with less heterogeneities than a thick specimen. Then this thin blank is reinforced by mounting it with resin on a wooden mount with a rear handle for the polishing process. A finished/polished mirror blank from Aranmula consisted of 32.5% tin (Table 1), approximating the composition of the pure delta compound of 32.6% tin ($Cu_{31}Sn_8$). Figure 1 is the etched colour photomicrograph of a sample of the mirror alloy from Malakkara, showing the predominance of the whitish/silvery delta ($\delta$) inter-metallic compound ($Cu_{31}Sn_8$), which remains more or less unetched by the etchant (ferric chloride), while minor amounts of the bluish etched network represents the alpha plus delta ($\alpha + \delta$) eutectoid. This figure well illustrates how the silvery-white colour of the specular delta alloy is responsible for the mirror effect.

## Closed crucible-cum-mould for casting mirror blank and its ventilation

To optimize the presence of the delta phase, a cleverly made jug-shaped crucible-cum-mould of clay (Figure 2) is used for the casting process, which we closely observed at a workshop in Aranmula during February 1998. Figure 2 shows a cut cross-section of the crucible-cum-mould for casting the delta high-tin bronze mirror encasing two pre-fired disc moulds with a gap for casting the mirror, and with a channel leading to a hollow cup where metal to be cast would be placed. The lower portion consisted of a two-piece clay mould connected to the neck through a channel, while the upper portion consisted of a hollow cup, wherein the metal pieces to be cast are placed and sealed with clay. The casting process essentially involves heating of the jug-shaped crucible-cum-mould top side down, so that the neck portion with the metal would get heated more and then when the jug is propped upright the metal flows into the space between the lower pre-fired disc moulds to get the cast mirror blank. The closed crucible process was used to prevent oxidation losses when the metal is cast and also to minimize the formation of an oxide skin, which would be detrimental to the polishing of the fine mirror blank. The two oval, pre-fired discs of clay of about 1.5 cm thick and 7 cm long were separated by small spacers, made of broken pieces of a couple of square millimetres of the brittle alloy to be cast, to leave a 3 mm gap within which the blank will be cast. A crucial

**Table 1.** Composition and hardness of Aranmula $\delta$ bronze mirror and of some ancient and modern $\beta$ bronzes from southern India

| Object | Cu (%) | Sn (%) | Total (%) | Hardness | Analysis of higher tin phase | Analysis of lower tin phase |
|---|---|---|---|---|---|---|
| Polished mirror blank, Aranmula, Kerala (bought in 1991) | 64.73 | 32.47 | 97.20 | 480 VPN | 32–34% Sn<br>Predominant matrix of whitish delta ($\delta$) phase | 26–27% Sn<br>Bluish alpha plus delta ($\alpha + \delta$) eutectoid phase |
| Mirror alloy, Malakkara, Kerala (obtained in 1992) | 66.91 | 33.39 | 100.29 | 500 VPN | 32–34% Sn<br>Predominant matrix of whitish delta ($\delta$) intermetallic compound phase (32.6% Sn) | 28% Sn<br>Bluish alpha plus delta ($\alpha + \delta$) eutectoid phase |
| Bowl purchased in Payangadi, Kerala (1991) | 77.65 | 22.54 | 100.33 | Beta ($\beta$) phase: 313<br>Alpha ($\alpha$) phase: 203 | 22.5–24% Sn<br>Predominant matrix of needles of martensitic quenched beta ($\beta$) phase | 21.5%<br>Lesser islands of alpha ($\alpha$) solid solution |
| Jug, Adichanallur, Tamil Nadu, 1st mill. BC | 77.61 | 22.92 | 100.75 | Beta ($\beta$) phase: 350 | 24.5–24.8% Sn<br>Predominant matrix of needles of martensitic quenched beta ($\beta$) phase | 16% Sn<br>Very small islands of alpha ($\alpha$) solid solution |

All the analyses were done by electron probe microanalysis (EPMA) on polished cross-sections of mounted speciments, using JOEL Superprobe JXA-8600 at 20 kv with ZAF correction within instrumental accuracy of 1% over 100%. The EPMA results were averaged over 10–15 measurements taken along the cross-section with probe diameters of 10–50 μ. Elements not listed are trace (i.e. below 0.1%) or below detection limits. Analysis and microstructural study was undertaken at Wolfson Laboratories, Institute of Archaeology, London.

process is the application of a fine slip on the inner surface of the moulds. According to the craftsmen, the slip, which is applied as liquid, is made by straining through linen the finest grade of alluvial clay-mixed cow-dung paste. The slip of about 1–2 mm thickness (Figure 2) when fired, would give the smoothest layer against which the mirror blank would be cast, while the presence of cow dung would help form a fine charred carbonaceous layer which would adsorb the gases inside the mould and give the finest possible casting. The pre-fired, almost brick-like disc moulds are then bound with iron wire and then jug-shaped crucible-cum-mould of clay is modelled around it, with a hollow channel leading to the cup into which metal to be cast is placed (Figure 2), and then the jug-shaped crucible-cum-mould is left to bake in the sun and harden.

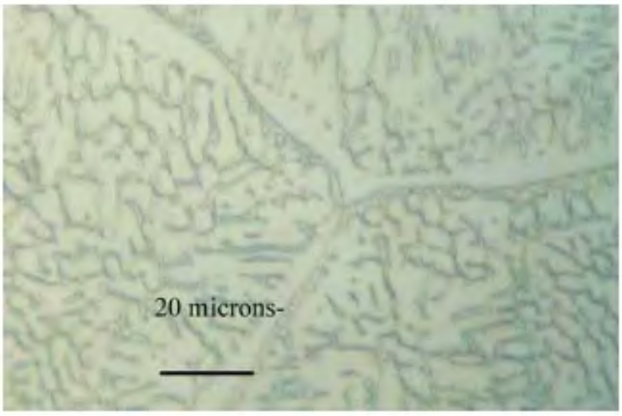


**Figure 1.** Photomicrograph showing microstructure of delta high-tin bronze mirror alloy (1000×) etched in ferric chloride.


**Figure 2.** Cut cross-section of crucible-cum-mould for casting delta high-tin bronze mirror.

A roughly cast ingot, about 13 cm long and 3 cm wide, of the delta bronze alloy was made by sand casting, which was then broken into pieces with a hammer and stuffed in the open cup inside the neck of the now dried crucible-cum-mould. We then noticed some crucial steps which explain how despite the use of the closed crucible process, measures were taken to ensure that the gases trapped inside the mould could escape, which could otherwise result in porosities in the casting. A fine long strip of cotton/straw rolled in fine cow-dung paste was made and placed such that it led all the way from the hollow channel inside, which connected to the space between the discs for casting the blank, to the exterior of the mould and then was left open to air (Figure 3). As the mouth of the crucible-cum-mould was being packed with wet clay, a fine piece of linen cloth soaked in a mixture of alluvial silt and cow-dung paste was sealed onto it (Figure 3) and then packed with more wet clay until a smooth, almost spherical mud cap was provided onto the crucible-cum-mould. The cotton cloth sealed onto the cap of the mould and the long cotton strip with cow-dung paste would perhaps serve the purpose that when the finished crucible-cum-mould is heated they would undergo combustion and thus enable ventilation of the mould. Thus the gases trapped inside the space where the blank is to be cast would have a chance to escape; which could otherwise result in a flawed blank with porosities or even bursting of the mould due to expansion. Furthermore, the straw/cotton roll would act as a burning wick, which while burning would ensure reducing conditions in the closed-crucible cup by getting rid of some of the oxygen and hence minimize the formation of a thicker oxide skin, which would be more problematic to polish away. S.S. observed the use of such a burning cloth at the mouth of a casting for a metal lamp at Irinjilakuda. Indeed, the 12th century Deccan text of the Manasollasa on the casting of metal icons also talks of a lighted wick being held near the sprue at the time of casting, which could have served a similar purpose.

**Figure 3.** Crucible-cum-mould being sealed with cloth dipped in silt and straw/cotton wick.

## Heating alloy in inverted crucible-mould, cooling in mud and casting blank

For the casting process, the closed clay crucible-cum-mould was held using a pair of tongs with the neck facing downwards and heated using coconut husk as fuel in a cubical brick hearth about a foot square and high. Use of coconut husk ensured even and controlled heating of the mould, where more husk could be added when necessary. The melting point of bronze of 30–35% tin alloy is around 745–760°C. While the electric or rotary blower was used continuously for the melting process, the flames were skillfully fanned with a mat made of coconut leaf strips, coconut husk was added into the hearth and crucible-cum-mould was periodically checked. The whole process from getting a good fire going to heating the inverted crucible-cum-mould took at least 45 min to an hour. The crucible-cum-mould was pulled out when the mouth, neck and only a quarter of the lower jug-shaped region was red hot.

Then, in an interesting cooling process, the red hot mouth containing the crucible of the inverted crucible-cum-mould was subjected to something akin to a 'mud-quench', where wet mud was packed around the mouth (Figure 4) for a few minutes. This might have had the effect of cooling down the molten metal slightly, so that the metal was not superheated and that the temperature difference between the molten metal and the rest of the cooler two-piece mould was not too much so as to prevent turbulent flow; which could in a normal situation cause problems when casting with impregnation of metal into the mould.

This process of packing wet mud was done till the red heat had completely dissipated, a blackish glaze had formed and the liquid metal in the crucible cup cooled down a bit. Then the inverted crucible-cum-mould was tipped over into the upright position and swirled around gently. The bottom half of the jug of the crucible-shaped mould was packed in mud, which would also help cooling to proceed at a uniform rate. The top vitrified/glazed mud cap was broken-off with a hammer exposing the now rose-coloured metal in the neck to air-cooling (Figure 5).

Apart from the packing of the heated crucible-cup in cooler mud described before, this process of exposing the metal in the neck to air could have also led to progressive and uniform cooling under usual or non-equilibrium conditions. Indeed this is consistent with the fact that the copper–tin phase diagram[6] indicates that for a solidifying bronze of 32–34% tin under full equilibrium or slow cooling conditions, the delta phase forms between about 586 and 350°C; however the phase diagram therein indicates that under non-equilibirum or usual casting conditions, which are faster than equilibrium, this delta phase is found at room temperatures. There does not seem to be any attempt at deliberate slow cooling of the alloy, but rather the opposite. Here our observations disagree with those of Pillai *et. al.*[7], who proposed that the Aranmula mirror blank was made by extremely slow cooling. The composition they broadly reported for a mirror of 30% tin was slightly lower than our observations which were made by repeated and detailed electron probe micro-analysis (EPMA) of 32–34% tin and which is closer to the composition of pure delta phase.

## Polishing the delta high-tin bronze mirror with the same powdered, brittle, hard alloy

The cast oval blank, about 7 cm long and 3 mm thick, which is retrieved by breaking the mould, is mounted in heated resin onto a wooden handle, which would reinforce this brittle alloy during polishing (Figure 6). It is then polished and lapped for about 2–3 h a day over four or five days over hessian and velvet cloth placed on a flat wooden board to get a mirror finish. The thin blank also

**Figure 4.** Inverted crucible-cum-mould with the red hot mouth being packed with mud.

**Figure 5.** Upright cut crucible-cum-mould partly buried in mud.

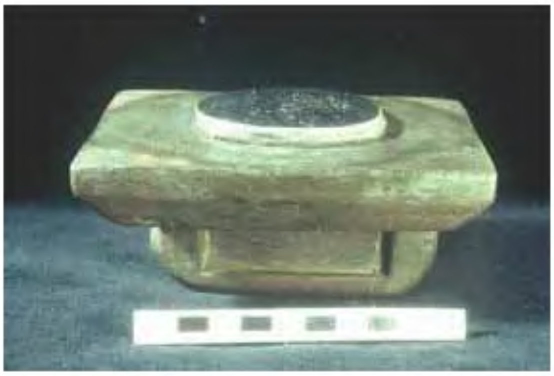

**Figure 6.** Cast oval (3 mm thick) blank of silvery delta high-tin bronze mounted with heated resin onto a wooden mount, to be polished to get the mirror effect.

helped in even polishing. The hardness of the delta bronze alloy, at about 500 VPN (Table 1), being harder than even normal steel (400 VPN), enabled the thin mirror blank to be polished almost entirely free of distortion. Ingeniously, the hard mirror alloy is itself used to give the mirror a final polish, as it can be easily powdered being highly brittle. The alloy is ground to powder with a grinding stone, mixed with gingelly oil as a suspension and applied onto the hessian cloth, and then the mirror blank is lapped on it by polishing it flat. This would serve to smoothen out and fill in any defects in the cast blank with the same alloy to give the best possible mirror finish. Such mirrors yield a precise point image, as they do not suffer from blurring due to refraction through glass encountered in glass mirrors. This indicates the high level of technological accomplishment in isolating the reflective intermetallic delta compound.

## History of the Aranmula mirror: Probable local origins

Apart from technological significance, this waning handicraft tradition of Aranmula also has had considerable sacred significance. The Aranmula mirror, known as 'valkannadi' in Tamil and Malayalam, traditionally made up one of the eight auspicious articles or 'ashtamangalyam' set of the wedding trousseau from the Nair and Namboodri communities. A Kushan period Jain votive tablet[8] (1st–2nd centuries CE) included a mirror as part of the 'ashtamangalyam' set. A sculpture from the Hoysala temple at Belur, Karnataka (12th century) depicts a 'madanika' or dancer looking at a mirror and admiring herself. Intriguingly, her mirror resembles the thick wooden polishing mount (Figure 6) with a rear handle from Aranmula onto which the mirror blank is fixed. Indeed, one may speculate that this could have in itself been used as a finished mirror as opposed to the current practice of mounting the mirror blank into a brass frame with a handle. The making of the Aranmula mirror has been secretly guarded by the craftsmen or 'acharis', who often say they are the 'last practitioners'. Discussions with craftsmen indicated that they believe the mirror alloy has an indigenous origin.

## Links with high-tin beta bronze usage in musical instruments and age-old vessels

As pointed out earlier, the unleaded delta bronze mirrors of Aranmula are technologically distinct from mirrors elsewhere and may rather draw from a longstanding Indian familiarity with unleaded binary high-tin bronze. Metallurgical investigations were made by S.S. on vessels from Iron Age burials and megaliths from the Nilgiris and Adichanallur in Tamil Nadu (Table 1), datable to the early to mid 1st millennium BCE[9]. These were found to be wrought and quenched high-tin beta bronze with around 23% tin, ranking amongst the earliest and most extensively wrought and elegant examples known in the world, with some having rims of 0.2 mm thick and others with fluted shapes and floral decorations. Due to the formation of a high-temperature plastic beta ($\beta$) intermetallic compound phase of a composition of 22.9%, the beta bronze alloys can be hot-forged, while quenching in water results in retention of the martensitic beta phase and prevents the formation of the embrittling delta phase eutectoid which forms under usual cooling conditions. This yields improved the properties of golden lustre, musicality, toughness and corrosion resistance. Vessels (Table 1) and cymbals of wrought and quenched high-tin beta bronze are still made in Kerala in a fashion similar to the megalithic vessels as documented earlier by the authors.

Mirrors have also been uncovered from the Nilgiri cairns and Adichanallur burials from Tamil Nadu, of the early to mid first millennium BC. A specimen of unleaded 30% tin bronze was reported from the Nilgiri cairns[10]. From Sonepur in eastern India, an early historic specimen of 32.4% tin-bronze was reported[11]. Old slags from co-smelting copper and tin ores have been reported from Karnataka[12], which might suggest exploitation of minor local tin reserves in southern antiquity. Two unleaded bronze samples of 22% and 26% tin were reported from the Indus Valley site of Mohenjodaro (ca. 2500 BCE)[13], although they might be accidentally alloyed. Although flat bronze mirrors are found from Indus sites such as Quetta, these do not seem to have been analysed and are much more likely to have been of copper or low-tin bronze. However, from the Bhir mound in Taxila, Pakistan, a binary high-tin bronze mirror of 25% tin was uncovered[14]. Thus it is probable that the Aranmula mirror-making process evolved out of longstanding metallurgical traditions prevalent in the Indian subcontinent for the use of bronzes of high tin content. It is heartening to note that recently this skilled and unique mirror craft from Aranmula was awarded a Geographical Indicator (GI) patent in India.

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# Satellite and ground-based ULF/ELF emissions observed before Gujarat earthquake in March 2006

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**Recent years have evidenced observations pertaining to electromagnetic emissions that are detected during the course of a seismic event. In this article, we have carried out a study related to seismo-electromagnetic emissions that were detected as perturbations in the ionosphere before the Gujarat earthquake which occurred on 7 March 2006, of magnitude 5.5 on the Richter scale. The epicentre of this activity was in the remote Rann of Kutch area near the border with Pakistan ($M$ = 5.5, lat. 23.78°N, long. 70.90°E, 18:20:46 h UT, $d$ = 10 km). Strong electromagnetic emissions have been observed with the help of the DEMETER satellite in the ELF (extremely low frequency) electric and magnetic components pertaining to the seismic activity. Complementarily, we have also studied the ground-based data of ULF (ultra low frequency) magnetic field and found significant enhancement of polarization ratio employing the LEMI-30i search coil magnetometer at the Department of Physics, Barkatullah University, Bhopal. The analysis of satellite as well as ground-based data suggests significant emissions that were observed before the Gujarat earthquake.**

**Keywords:** DEMETER satellite, extremely low frequency, search coil magnetometer, ultra low frequency.

THE subjective study of seismo-electromagnetism deals with the electric and magnetic field perturbations that are observed during a seismic activity. Broader investigation of the seismo-electromagnetic effects involves studies related to magnetic and telluric fields[1], ionospheric perturbations[2], nightglow observations and generation of electromagnetic emissions from DC to high frequency (HF) range[3]. Long-term studies and manifestations reveal that electromagnetic anomalies are likely to be observed a few hours to a few days before moderate and strong seismic activities[4]. Significant contributions have been based on observations of ULF/ELF (ultra low frequency/extremely low frequency) emissions related to seismic activities. Studies[5–7] reveal enhancement in ULF magnetic field before the famous Loma Prieta earthquake of 1989, performed with a ground-based magnetometer installed in the seismically active areas. More recent works in this field involve analysis of the polarization ratio (ratio of vertical magnetic field component to horizontal magnetic field component) using ground-based magnetometers[8–10] having observed ULF magnetic field perturbations before earthquakes. Other aspects of evaluating the seismogenic ULF/ELF perturbations involve studies made with the help of LEOs (low earth orbiting satellites) to observe perturbations at the ionospheric level[11–14].

In this article, we discuss some important results where we have observed electromagnetic emissions before the Gujarat earthquake (the epicentre was in the remote Rann of Kutch area near the border with Pakistan), that occurred on 7 March 2006 ($M$ = 5.5, lat. 23.78°N, long. 70.90°E, 18:20:46 h UT, $d$ = 10 km). These emissions have been observed in the ionosphere using the data from DEMETER (Detection of Electromagnetic Emissions Transmitted from Earthquake Regions) satellite in the ULF/ELF range. Further, we have also performed observational analysis for the same event implementing ground-based magnetometer (LEMI-30i) for measuring the magnetic field variations during the earthquake. The objective is attributable to the reporting of an event where electromagnetic emissions are observed through both ground as well as satellite-borne technique.

## Method of observation

Studies reveal that installation of ground-based magnetic sensors such as magnetometers is important for measuring the magnetic field changes associated with earthquakes and for studying a particular area consistently which is hit by seismic shocks[15–17]. Satellite-based data studies are advantageous as they provide a global coverage of the seismic zones.

### *DEMETER satellite*

DEMETER is a microsatellite which was launched on 29 June 2004 from Baikonour, for studying the ionospheric perturbations linked with seismic activities. The scientific

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