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BRONZE ICONS

Baldev Raj, B. Venkatraman, R. Balasubramaniam* and V. Jeyaraj*
Indira Gandhi Centre for Atomic Research, Kalpakkam - 603 102, India
*Government Museum, Chennai – 600 034
E-mail: bvenkat@igcar.gov.in

ABSTRACT

Art objects are scientific marvels which reflect the history, tradition and cultural heritage of a country. Investigations on art objects are undertaken for scientific and comprehensive fingerprinting and authentication and also to help in restoration/conservation. One of the outstanding art objects of India is the South Indian Bronzes. Famous for their aesthetic beauty, iconometry, iconography, and casting quality of high order, they are standing examples of the fusion of technology with cultural traditions. This paper outlines the lost wax process used for making these bronzes and also the results of the non-destructive analysis carried out on more than 100 rare South Indian Bronzes. Radiography revealed the presence of porosities as the major defects while X-ray fluorescence revealed that copper is the major constituent of all icons with additive elements such as Sn, Pb, and Fe present with varying compositions. Microstructural studies revealed the presence of large pores and cavities combined with gray phases and globular particles. Analysis also revealed that the ancient science and technology of casting the icons was rather qualitative, empirical and adhoc with rather small amount of theoretical underpinning.

1. INTRODUCTION

Benjamin Rowland, rightly pointed out that " .... Indian Art of all periods is close to life, not only to the life of the Gods but to all creatures on Earth....Although the proportions, pose and gestures of an image were unquestionably based on a strict metaphysical canon designed to ensure its fitness as an object of worship, within this framework the figure was made with an understanding of actual human anatomy, not only in its general articulations, but also in the maker's concern with connoting the essential character of the flesh in terms of stone or bronze...". Thus of all the metallurgical accomplishments of South India, the bronze icons are among the finest artistic treasures cherished by national, international and private antiquarians around the world. Famous for their aesthetic beauty, iconometry, Bronzes are excellent examples of the fusion of technology with cultural traditions. The objective of this paper is to provide the readers with

(a) an outline of the ancient casting practice followed by the sthapathis,

(b) take a comprehensive look at the results of the scientific investigations using NDE techniques carried out by the authors on more than 100 icons belonging to the Pallava, Chola, Vijayanagara and modern periods,

(c) elucidate certain misnomers with respect to the composition of bronzes and

(d) highlight the fact that in spite of the heuristic approach, empirical procedures and very limited tools, our ancient master craftsmen had been able to achieve very sound castings.

2. THE MAKING OF AN ICON

The icons (solid or hollow) were made by '*Cire Perdue*' or ' lost wax' process. *Cire* in French means 'wax' and *perdue* means 'lost'. The process in ancient Hindu scriptures, such as *Manasara*, has been referred to as *madhuchchista vidhanam* (*madhuchchista* means bees' wax). The wax model prepared according to the *Agamic sastras*, served as the core of the operation and was 'lost' or drained out before the actual casting took its form after the model.

Each and every icon is made in full accordance to the *shilpasasthras* (texts that grammatically define the form and style of the icons)[1].

The *shilpasasthras*, give a broad outline of how each God or Goddess is cast into icons. They mention usually about the macro-features of the idol. The micro-features of the idol, such as the type of clothing, type of hair style, the standing or sitting posture, the style of displaying wrists, palms and hands (known commonly as the *hasthas*), the look on the face, expression of emotion, etc. are entirely left to the imagination of the artisan. If one scans a number of bronze icons made during this ancient period, it is this aspect that speaks about the cultural and technical excellence of any artisan. However, it is a commonly accepted fact that sthapatis belonging to one particular school of casting tend to cast icons in a particular fashion, that helps us in categorising the styles and finding the period or age of the icon.

The various sequential steps in the lost wax casting, as practiced by the ancient sthapatis are listed below :

a. Making of the odiolai

b. Preparation of the wax

c. Getting ready the wax model

d. Making the mould over the wax model

e. Heating the mould, melting and draining the wax

f. Getting ready the liquid metal alloy and heating the mould to higher temperature

g. Pouring the liquid metal alloy inside the mould

h. Cooling the mould and opening it

I. Bringing the cast icon outside followed by finishing, engraving and polishing and

j. Installation and opening of the eyes of the icon.

Step (j) is carried out, in case, the icon is to be worshipped. The sthapatis have developed over a period of time, a heuristic relationship between the amount of wax used in making the wax model and the amount of molten alloy that needs to be used for making the icon. That no other analytical relationships are used for this purpose, is a testimony to the empirical expertise of these sthapatis. Similarly the heating up of the clay shell to a specific temperature (which is usually not measured), before pouring the molten alloy, speaks of the qualitative yet comprehensive empirical knowledge of ancient sthapatis. These ten steps in the making of the cast icon, are exactly the same as practiced in Swamimalai a small town in Tamil Nadu today with minor variations between the methodologies and those prescribed in the *Shilpasastra* texts . These variations are not much in the actual method of casting, but on the rituals to be performed, before, during and after casting. A detailed stepwise description of the casting process can be had from ref. 2. A brief outline of the same is also presented in the paper by Pillai et al.[3] published in this special issue of the journal.

3. STYLES, INTRICACIES AND FORM

These ancient south Indian bronzes bear the mark of classical tradition in smooth modelling, aesthetic decoration and high proportions. One of the most striking aspects of these bronzes is the true and authentic representation of human and animal anatomy, and other accessories to the last detail. The expertise of the *sthapatis*, in bringing out the finer details of each part of the icon has been much appreciated, and is the prime reason for the value of these icons.

The initial wax mould of every icon is made with great care, with due attention to the structure and size of its parts. For each of the parts, an empirical association is made, which intuitively suggest to the artisan as to how the final proportion of the part should look like. These empirical associations are based on keen observations on the human (or animal, as the case may be) anatomy, with a purpose of replicating the part to the last perfect detail. For example, when a *Kannagi* statue was cast for worship, traditional descriptions of the icon were not available and the *sthapati* made a number of models based on his imagination and in tune with the features described in literature. From these models, one of them was chosen for the final wax model. These associations are called *lakshanas* and there are 32 of them mentioned in the *Agama Sastras*. However, these associations are not scriptural constraints but offer the artisan a broad yet accepted guideline. The last word in any such representation of a part lies with the artisan himself offering him the highest manoeuvrability of his creative genius. These associations, for some of the human parts are given in Table 1. The Tamil names of various terms are given in italics.

The most important aspect that gives a unique signature to any icon, and its style, is the fact that each casting process is non-repeatable, since both the wax model and the clay shell are lost forever, after each icon is cast. It is because of this fact, that it is impossible to find two icons (cast in this process) to be identical. Each icon thus becomes a designer icon. Hence the method is also called the master technique. The making of images in this process is indeed laborious. But the importance of this method cannot be overestimated when it is realised that each item is characterised by a rare individuality and provides the possibility of continuous improvement, aesthetics and technology - a hallmark achieved by ancients as a matter of course and being advocated by modern quality management gurus like "Deming", "Taguchi" or "Joseph Jurian".

4. CHOICE OF THE ALLOY - WHY BRONZE ?

An interesting aspect about the icons under study is that most of them have been cast only in bronze. The reason for this could be many, the most important being [a] castability, [b] workability after finishing the casting, [c] polishability, [d] melting point of the

Table 1
VARIOUS EMPIRICAL ASSOCIATIONS OF THE PARTS OF AN ICON

The Part / The Icon	The Association or the *Lakshana*
Leg (particularly those of females)	*Kendai* Fish
Lord Shiva's face	Hen's Egg
Lord Vishnu (S) 's face	Duck's Egg
Kataka Hastam (*Hastam* is the representation of the human palm and fingers, specifically in the dance postures; these are also called *mudras*	Crab
Nose	Gingily (*Thuthi*) Flower
Upper Lip	Bow
Lower Lip	*Kovai(T)* Fruit
Eye brows	Neem Leaf
Eyes	Fish
Ear	Lily Flower
Chin	Mango Stone
Neck	Conch Shell
Thighs	Banana Tree Trunk
Knee Cap	Crab
Shoulders	Elephant's Trunk or Banana Tree Trunk
Male figure / torso	Bull's Face
Female figure / look	Deer's figure and looks

alloy (requirement of large quantity of molten alloy) and of course [e] availability of raw materials, ore, etc.

From the sthapati's point of view, cast ability, workability, polish ability and melting point should have been the overriding factors. The shine what one gets in bronze is generally not available in brass and other alloys that were prevalent in those times. This also should have been a major reason for choice of the alloying additions for obtaining the desirable results.

The other important reason is the scriptural command of the Agamas, that prescribe metal to be used for casting idols for worship. For example, the ancient text Agnipurana states[4] that "one (image) made of wood gives greater merit than what is made of clay; one made of terracotta yields greater than a wooden one; one made of stone yields greater than (one) which is made of terracotta; images made of gold and other metals yield the greatest religious merit."

4.1 Composition of the Alloy - The Specifications

Though the term 'bronze' icons is used throughout the monograph, it must be mentioned that chemical analysis of the icons by the present and various other authors have shown that this usage may not be acceptable from a purely metallurgical viewpoint. Typical variations in composition is shown in Table 2[5].

It is to be noted here that the tin content of the icons are insignificant in some cases. The significance of the metal objects examination was the trace element analysis which was considered to play an important role in the technical excellence and finding the origin and age of the bronzes. However, Dr. Hall of Oxford University points out as "our experience at Oxford, in this field, tended to show that such analyses are a waste of time"[6]. This was so because extensive melting and reuse of scrap leads to a blurring of trace element identity. Most of the samples are taken from or near the surface, and the expected drawback of such analyses is that with passage of time, the composition of alloying elements vary at the surface due to their extensive interaction with the surroundings. All the above points make the characterisation study of the icons a very delicate and difficult job to be carried out.

At this juncture, it must be noted that in Tamil, majority of these icons are referred to as '*Cheppu Thirumaenigal*', meaning icons made of copper ('*Cheppu*' in Tamil means copper and not bronze). Bronze is known as '*Vengalam*' in Tamil. The *sthapatis* no doubt knew the existence of bronze alloy. If this is the case how did the term bronze icons come into force ? We infer that the term 'bronze' icons is a misnomer, used universally to refer to these ancient south Indian icons. However, in the absence of an uniform nomenclature, the colloquial term 'bronze' is universally used to represent even icons made with varying compositions and we follow the tradition.

It is also mentioned[7] that the *Agamas* mention the use of only gold, silver or copper for casting icons, and that most of the early bronze icons were made of either reddish or golden copper, with copper content being more than 90%. The quality and quantity of copper used declined from about 14th century A.D., with the knowledge of a number of alloying additions for achieving the desired characteristics of the icon.

Later, icons were also cast using '*Panchaloha*'. This term is derived from sanskrit in which "*Pancha*" means five and "*loha*" means metals. *"Formerly, these consisted of the following metals which were considered to be auspicious - copper, silver, gold, brass and lead. It is to be mentioned that brass is referred to as metal as copper and zinc were co-extracted as one entity. Gradually however, gold and silver were deleted for obvious economic reasons, although even today a client may commission an image to be cast in the original five metals for special devotional purposes"*[8,9]. The quantities of metal, wax and other raw materials required for each icon, depend on the size of the icon and are listed in Table 3. According to the empirical approaches developed by these *sthapatis*, for every gram of various materials required to produce the wax model, 8 grams (gms) of alloy were required (7.25 gms copper, 0.5 gms brass and 0.25 gms lead).

The bronze icons that are cast using the *lost wax* process can be classified broadly into two categories: those that are used (to be used) for worshipping and or *pooja* purposes and those that are cast mainly for ornamental purposes. The composition of the latter category is copper 82%, brass 15% and lead 3% [8],

Table 2
CHEMICAL COMPOSITIONS OF SOME ICONS[5]

Elements	9th century	13th century (Icon)	13th century (*Prabhavalli*)	16th century
Copper(wt%)	98.60	94.50	94.50	89.40
Tin(wt%)	0.88	1.10	1.80	3.40
Lead(wt%)	0.34	1.00	3.35	2.88
Iron(wt%)	0.13	0.05	0.10	0.52
Zinc(ppm)	15.00	40.00	103.00	2646.00
Antimony(ppm)	476.00	1747.00	5309.00	3095.00
Silver(ppm)	541.00	596.00	1659.00	823.00
Arsenic(ppm)	1295.00	1785.00	3341.00	1394.00
Nickel(ppm)	436.00	415.00	552.00	636.00
Bismuth(ppm)	85.00	164.00	503.00	351.00
Cobalt(ppm)	45.30	135.00	100.00	114.00
Manganese(ppm)	5.80	< 0.80	< 0.80	1.80
Total	**100.20**	**97.10**	**99.80**	**97.10**

whereas in the former category, gold and silver are added in proportions that are dictated by the *Vedas* and the *Agama Sastras*.

5. NEED FOR SCIENTIFIC INVESTIGATIONS

South Indian bronzes are scientific and art marvels which reflect the rich cultural heritage of our country. Scientific investigations on objects of cultural heritage are undertaken with a variety of objectives in mind. The most important of these include

1. Understanding the style, period, structure and metallurgy of these icons so that India's rich technological history is understood.
2. Assessing the condition of the icon to help in restoration and conservation

Table 3
RAW MATERIALS USED BY THE *sthapatis*

Category	Raw Materials
Primary Raw Materials (Metals and Alloys)	Copper, Brass, Lead, Tin, Zinc, Silver and Gold
Secondary raw materials (wax model preparation)	Bees' wax, dammar, paraffin wax, candle wax, groundnut oil and coconut oil
Tertiary raw materials (mould preparation and heating)	Charcoal, firewood, cowdung cake, metal wires, tamarind and clay

3. These bronzes famous for their aesthetic beauty and excellent craftsmanship are prone to thefts. These investigations help in scientific and comprehensive fingerprinting of icons needed for documentation and authentic identification when they are retrieved.

Scientific investigations of bronzes require an integrated approach. The most appropriate approach which can give solution to all the requirements is through the use of Non-Destructive Testing (NDT) techniques. NDT techniques as the name implies are techniques that have been developed to determine the quality of components without causing any harm or alteration to them. A variety of NDT techniques are available today, which are being successfully employed in various industries to assess the quality and ensure the integrity, safety and reliability of plants and components[10,11]. A few of these techniques have also been successfully applied for the investigation of objects of cultural heritage such as sculptures, paintings, monuments, etc. world wide[12,13,14,15]. Table 4 lists some of the major NDT techniques used for investigations on objects of cultural heritage and their capabilities.

In India, as part of the collaborative project between IGCAR, Kalpakkam and Govern,ment Musuem Chenai and funded by the Department of Science and Technology (DST), on fingerprinting of ancient South Indian *panchaloha* icons, a number of icons pertaining to the period between 9th century and 16th century AD belonging to the *Pallava, Chola* and *Vijayanagara* periods have been studied. Of the above mentioned NDT techniques, four had been identified as the major ones to be used for investigation, namely precision photography, X- and gamma radiography, X-ray emission spectrometry and in-situ metallography. While precision photography maps the overall icon and its intricate external features, radiography records the internal details, typical flaws and also provides information on the constituent and morphological elements and sequence of fabrication and repair. X-ray emission spectrometry provides information on the chemical composition of the icon while in-situ metallography characterizes its

Table 4
MAJOR NDT TECHNIQUES USED FOR AUTHENTICATION OF ART OBJECTS

Sl. No.	Techniques	Capabilities
1.	Precision Photography	Dimensions, measurements and record of intricate details
2.	Holography	3 - D Characterisation
3.	Moire Fringes	Contour Mapping
4.	Laser Excited Emission Spectrometry	Chemical Assay
5.	Mass Spectrometry	Chemical Assay
6.	Activation Analysis	Trace Analysis of elements
7.	X-Ray Energy Spectrometry	Chemical Composition
8.	IN-Situ Metallography	Microstructural Characterisation
9.	Radiography/Tomography	Internal Defects, Joints, Repair regions
10.	Physical Parameters Thermal Emf, Electrical Conductivity, Hardness	Characterisation of Material and Thermo-mechanical treatment

microstructure. Thus, on the whole, an icon is fingerprinted by the use of these techniques. Detailed analysis of these results also provides a deep insight into the metallurgical practices of yester years and helps to comment on many a misnomers on the basis of measurements and their analysis. The other techniques such as conductivity and hardness measurements lend a supporting hand in the investigations and lead to a better understanding and appreciation of the technology. In this paper, we present the results of the investigations carried out on more than 100 icons from the Govt. Museum, Madras. The Government Museum Chennai has the largest collection of South Indian Bronzes. Some of the rare bronzes investigated are shown in Fig. 1.

5.1 Results of NDT Investigations

5.1.1 Radiography

Icons are basically cast structures. During the process of casting, discontinuities or flaws are likely to be created due to a variety of reasons. Radiography is the best technique for the detection of internal features / flaws in castings. Depending on the casting process, the location of the defects if formed would be different in different icons. Thus, these defects can serve as authentic fingerprint of an icon. Duplication of these defects is not possible as the probability of the defect occurring in the same location and with the same geometric contours and area is extremely low if not zero. Apart from serving as fingerprints, the radiographs also serve as an indicator of the quality of the castings.

5.1.1.1 Experimental Technique

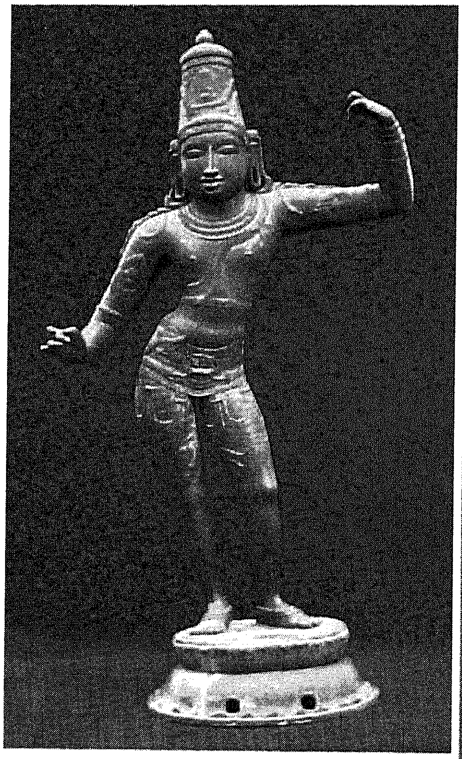
A typical icon has an intricate and complex shape with wide thickness variation and presents an interesting challenge to any radiographer. A wide range of radiographic parameters such as voltage, exposure, film types etc. are to be used to obtain the best possible radiographs. In the experimental campaign by the authors both X-ray and gamma ray sources were used. A 420 kV X-ray machine and a 200 kV X-ray machine were used for the examination of bronzes with a thickness range upto 50 mm while a Iridium 192 gamma source was used for the radiography of thicker bronzes such as Ardhanareswarar. Single wall single image technique was adopted in all the cases. To cover the thickness latitude present in the icons, multi film technique was adopted. Since the icons could be made available only for limited period of time (as they had to be removed from the Bronze Gallery), a novel multi exposure technique was adopted in which about 5 to 6 icons were exposed simultaneously. The radiographic parameters in this case had to be judiciously optimized for getting uniform densities on the radiographs.

5.1.1.2 Results of investigations

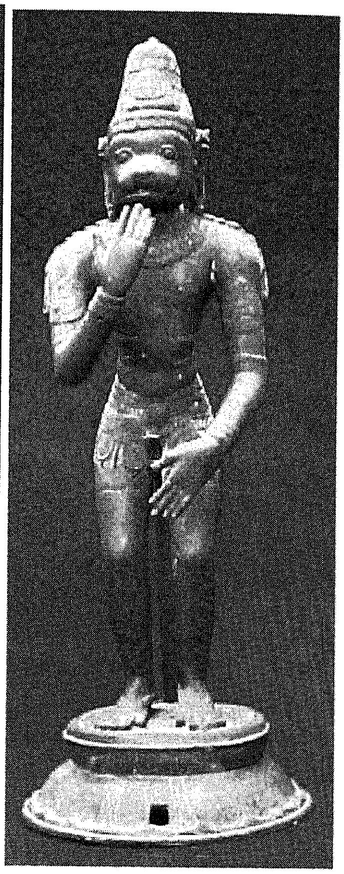
Detailed analysis of the radiographs of all the icons reveal many common and interesting observations

1. Most of the icons radiographed had very little defects in their main body. This is a pointer to the fact that the *sthapathis* of yester years had mastered the technology of lost wax process to perfection. This was also passed on by them to their next generation as revealed by the radiographs of the icons right from the 9th century to till date.
2. Defects if any in an icon were mainly porosities. Typical size of pores and voids range from 0.1 mm to about 10 mm depending on the size of the icon. Figures 2 - 3 are typical porosities detected in some of the icons.
3. In practically all the bigger icons, it has been observed by radiography that the main body of the deity, the pedestal and associated features like *Prabhavali* etc. were cast independently and were subsequently forge welded. Joints between the body and the pedestal were revealed in the radiographs. It was observed that reference studs were used to facilitate the alignment of the red hot individual parts of the icon during forge welding.
4. While all the icons had solid body, one small size icon was found to be hollow inside. It appears to have been cast in that way intently (Fig. 4).
5. Radiography also reveals if the icon has undergone repair at a later stage. Two typical examples are presented in Fig. 5.

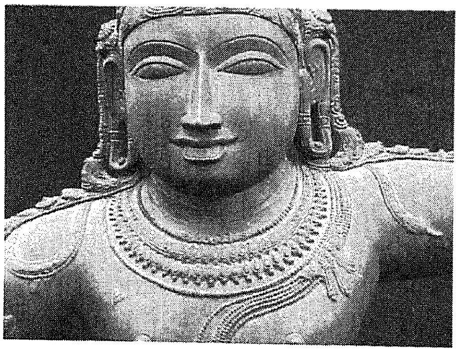
Ardhanareswarar – 11th Century



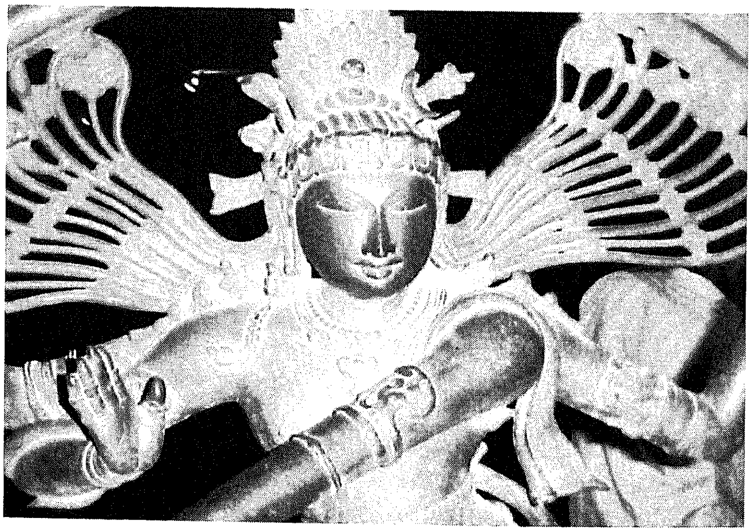
Rama 13th Century



Hanuman 12th Century

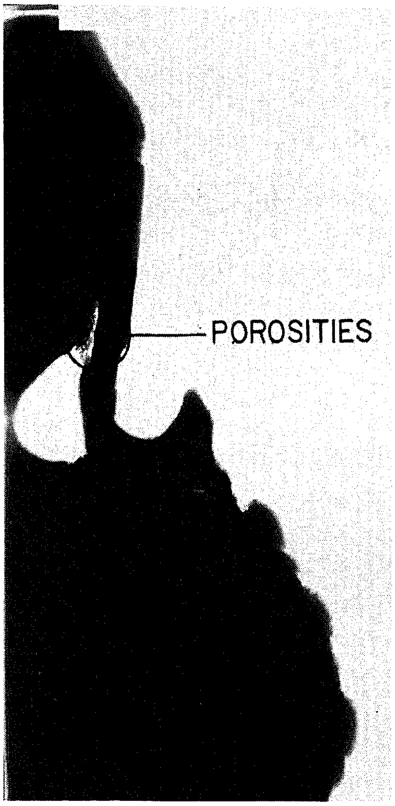


Closeup view of Rama. The sharp facial features, intricate ornamental design in the neck and the attractive smile enhances the icons artistic value.



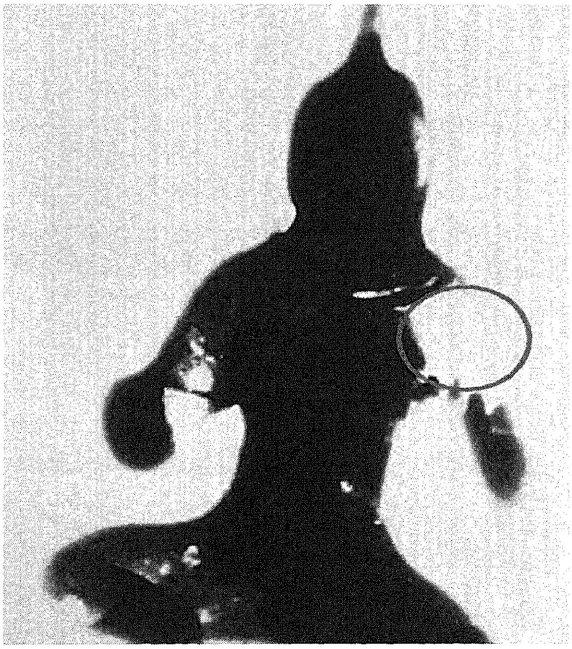
Nataraja – 12th Century

Fig. 1 : Some of the rare bronzes investigated at Chennai Museum



Photograph of hollow idol

Fig. 2 : Porosities in the earlobe of 16th century Vishnu icon



Positive print of radiograph

Fig. 3 : Porosities in the hand of a 13th century Nataraja

Fig. 4 : Radiography reveals hollow casting

(a) Radiograph of 9th century (Pallava) Vishnu. Repair in the leg region (indicated by an arrow) is revealed by radiography

(b) Photograph of idol

(c) Positive print of radiograph. Note the apparent discontinuity in the crown

Fig. 5: Typical repairs revealed by radiography

5.1.2 X-Ray Fluorescence Analysis

Study of chemical composition (signature) of the icon forms an important aspect in characterising (fingerprinting) the icon. Conventional chemical analysis needs some quantity of the material to be removed from the icon. Therefore we have to use specific methods where the icons and the patina which is formed on their surface as a natural and slow process over many years are not disturbed. X-ray fluorescence analysis is a completely non destructive method of qualitative / quantitative analysis for chemical elements based on measurement of the energy and intensities of their X-ray spectral lines emitted by secondary excitation. The primary X-ray beam irradiates the specimen, exciting each chemical element to fluoresce (i.e. emitting their characteristic X-ray). The energy of each element's X-rays is unique to the element (basis of qualitative analysis) and the intensity is a measure of the element's concentration in the sample (basis of quantitative analysis). The samples are not altered or damaged by the analysis. So this technique is a completely non-destructive technique for chemical analysis.

5.1.2.1 Experimental Details

Asoma 200/400 isotope based portable XRF system had been used for the investigation of the bronzes. This instrument has a remote measuring head attached to the console. There are two isotope sources Curium-244 (^{244}Cm -30 mCi), and Americium-241 (^{241}Am - 20 mCi) for primary excitation of the sample. The X-radiation fluoresced and scattered from the sample is detected by a high resolution, gas-filled proportional counter. Each photon absorbed by proportional counter gives rise to a pulse, whose height is proportional to the energy of the photon. These pulses are sent to a multi channel analyser (4096 channels). The data is acquired by a PC for further analysis.

Since the complex shapes of the icons with varying contours and flatness affect the efficiency of data collection, relatively flat surfaces of the icons were chosen for the analysis. Different regions within the icon such as crown, face, belly, back, hand, leg etc were also studied. The XRF probe was oriented so as to have maximum contact area on the surface of the icon.

Both (^{241}Am and ^{144}Cm) were used for excitation, as each of the source is sensitive in exciting a different set of elements. Americium source is used to analyse tin, lead, antimony, bismuth and silver. Curium source is used to analyse copper, zinc, iron, nickel, gold, arsenic and cobalt. Two separate spectra are recorded for analysis. An exposure time of 160 seconds has been chosen for this study so that signal to noise ratio is good. Appropriate energy calibration and background correction were incorporated during the analysis.

5.1.2.2 Results of XRF Analysis

Twenty icons belonging to Chola period were analysed. Fig. 6 is a typical XRF spectra obtained. In order to preserve the antiquity of the icon, XRF analysis was confined to the surface only and the interpretations are based on these results only.

(a) The major constituent in all these icons is copper. The additive elements tin, lead and iron were present in all the 18 icons, with varying compositions. This indicates the variation in the metallurgical practices prevalent in the Chola period.

(b) Change of composition from icon to icon: copper composition is varying from 68% to 97%, tin from 1.72% to 12.79%, lead from 1.20% to 18.35% and iron from nil% to 5.26% (except in one specific case.

(c) Change of composition was observed from region to region within the same icon. This variation was within about 10% in general.

(d) In a few cases large deviation was observed in some regions (ex: idol no. 1526/89 seat region, and 1886/96 pedestal region). This may be due to one or more of the following reasons :

  i. localised differential leaching when the icon was buried,

  ii. employing a different melt for that portion of the icon at the time of casting,

  iii. differential segregation of alloying elements during solidification of cast icon.

  iv. In general the patina appeared whitish where lead content is observed to be high.

  The patina is greenish where the tin content is high.

(e) In one of the icons, in the pedestal region, Fe was the major element unlike in other places. This is adjacent to a tie-hole. The tie-holes are used to tie the icon to a platform during festival processions. It is likely that the icon was buried along with the iron support rod in the tie hole. In due course the iron rod might have disintegrated and enriched the adherent soil with Fe. An alternative possibility is that this may be due to a subsequent repair where Fe rich alloy might have been used. True picture can come out only if the metal core beneath the surface is analysed.

(f) Gold and silver could not be detected. This may be due to their absence in the patina. Due to their noble nature, gold and silver might not have participated in environmental interactions.

5.1.2.3 Effect of Patina

Most of the icons are covered with patina on the surface. The thickness of the patina is of the order of 100 to 300 μm. The penetration of X-rays is confined only to 50-1 00 μm. Thus there is every possibility of X-rays seeing only the patina but not the actual metal surface. To study the effect of patina on the XRF analysis, the region of analysis was polished in three icons to remove the patina and expose the metal body of the icon. XRF analysis was done before and after removing the patina.

It was observed that the removal of the patina has an increase in the overall counts. It can be seen that no new element is observed in the XRF spectrum after polishing. In general the copper content is more in the metal of the icon compared with that in the patina. Cu content analysis made on the patina is underestimated in the range 1.3% to 12.4%. The other elements particularly lead and tin are overestimated in the patina. Overestimation is to the tune of 13.8% to 61.3% for Pb and 10.3 to *40.07%* for Sn. Fe has shown significant variation only in one case.

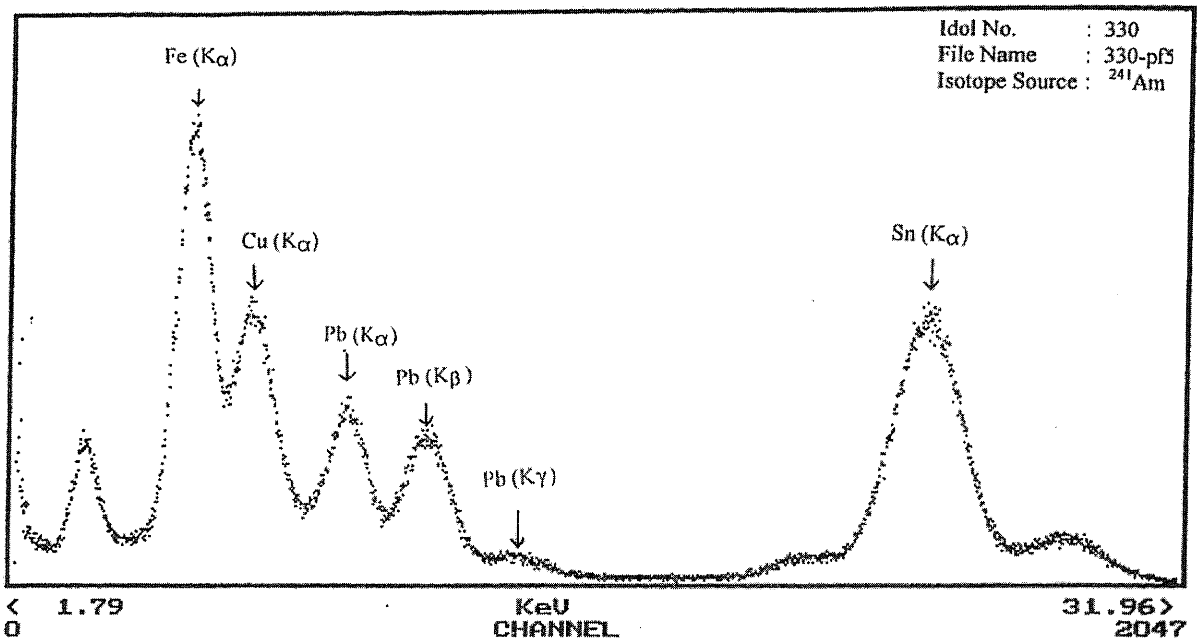


Fig. 6 : Typical XRF spectra

This variation in the elemental composition in the patina compared with that in the icon is due to differential leaching of the elements. This leaching is from the metal to adherent soil and from adherent soil to the surroundings when the icon is buried.

The variation in patina on metal composition is a very significant and unique fingerprint of great value as it cannot be duplicated by any proven scientific methodology. Its value is similar to unique defects in icon casting and both these fingerprints are completely independent of each other.

5.1.3 In-situ metallography and Microstructural characterisation

In-situ metallography was done on selective and inconspicuous regions of the icons due to constraints like retaining the antiquity of the icon. The replica technique was adopted. All the icons showed typical cast structures. Both fine and coarse grain structures were observed indicating that cooling rates in the casting process were different. Photomicrographs of some of the pedestals indicated partially /fully recyrstallised grain structure indicating working on the pedestals after casting them. Casting defects were observed in the microstructures of all the pedestals. They range from distributed porosity to interdendritic cavities and blow holes. Compared to these, the microstructure of the main icon indicates better cast structure. A typical microstructure of a 15th century *Vishnu* icon is indicated in Fig. 7. Figure 8 is the interdendritic cavity observed in the pedestal of the same icon. It is well known that from the microstructure it is possible to get an idea of the cooling rates by observing the dendritic arm spacing under magnification using a scanning electron microscope. However, these cooling rates vary depending on the addition of alloying elements and the casting procedure adopted by the sthapatis. Thus, from the microstructures obtained from icons

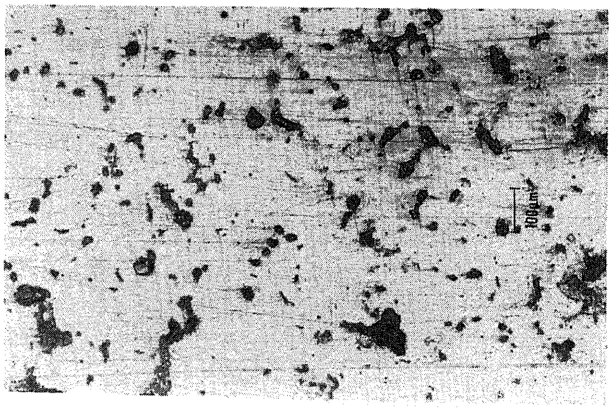


Fig. 7 : A typical microstructure of a 15th century *Vishnu* icon

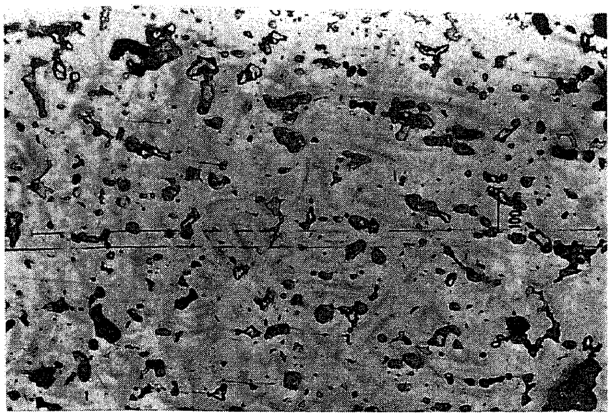


Fig. 8: Interdendritic cavity observed in the pedestal of the 15^{th} century Vishnu icon.

belonging to different periods, it is possible for us to get an idea of the relative cooling rates of these castings.

In general, the microstructural studies of the icons have revealed that very large pores and cavities combined with gray phases and globular particles are present. However, the present day Swamimalai icon showed small and medium size pores and particles which are homogeneously and uniformly distributed.

5.1.4 Results of other NDE techniques

The microhardness measurements indicated that all these icons fall within a range of hardness values indicating insignificant variations in their strength values. The Secondary Ion Mass Spectrometer (SIMS) analysis showed interesting observations with respect to the surface composition and distribution of alloying elements. Lead was found invariably enriched on the surface of all icons irrespective of the changes in their chemical composition as shown in Table 2. Such an enrichment of lead was reported by R. Cesareo et. al[16] while analysing several bronze icons by X-ray fluorescence method. Also depletion of tin was noticed for all the samples, and the enrichment of both aluminium and carbon is also observed. XRD analysis of the soil (Table 5) indicated that main constituent of the soil is silica and cuprous oxide and in addition copper chloride.

The presence of copper chloride indicated that the soil is corrosive and contained salt. A large variation is noticed with respect to the presence of elements including copper. For example, one of the soil samples did not show any metallic element, the other two showed the presence of all elements. The chemical analysis of the icons (Table 2) showed the presence of copper, tin, lead and zinc in all icons. However, the zinc content is lesser in comparison with lead and tin. Iron, arsenic and antimony were also present in trace quantities. The other alloying elements like silver, bismuth and nickel were found in insignificant quantities. It is clear that apart from copper, tin, lead and zinc the presence of other alloying elements could have been due to their coexistence with copper ore. The ancient technologists were not using refined copper as this was invented only in 19^{th} century AD. The crude copper metal will invariably contain these elements in sufficient quantities. Lead is the most important alloying element[17] which can give important contribution to the casting technology of the bronze icons. The deliberate addition was demanded for the flexibility in the casting of the icons. The presence of lead which is not soluble in copper would fill up the cavities and increases the pressure tightness of the castings. In addition, during initial stages of corrosion, lead interacts with the surroundings to form lead dioxide, sulphate and carbonate particles which enrich the surface. In the ancient tin bronzes, the presence of tin was attributed to the use of copper ores containing tin stones [18]. Historical evidences show that the Sumerian civilisation was the first to develop high quality bronze articles during 3500 BC which contained about 10 to 15% tin. The tin content in the present alloys are about 1 to 5% falling in the solid solubility limit and hence the presence of delta phase compound $Cu_{31}Sn_8$ is ruled out. It has also been reported[18] that the cast bronzes containing more than 5% tin only will precipitate $Cu_{31}Sn_8$ unless it is extremely slowly cooled. In addition the presence of å-phase is not possible in these alloys as there is no thermal input of the order of 623 K for longer durations beyond 1000 hours to initiate such precipitation. It is deduced that the absence of above phases has improved the corrosion resistance of these icons. However, when zinc is added in small quantities to the bronze as in the present alloys, it goes into the primary alpha phase which would not significantly affect the corrosion resistance. The microstructure of the present alloys of Swamimalai icon have shown the presence of cored alpha-phase of Cu-Sn-Zn due to the long freezing range, with lead present as dark interdendritic globular particles in all alloys.

Table 5
XRD ANALYSIS OF SOIL SAMPLES OF BRONZE ICONS

Bronze Icon	SiO_2	Cu_2O	$Cu_3(CO_3)_2(OH_2)$	$Cu_2Cl(OH)_3$	Cu	Sn	Zn
Bhudevi - PB	✓	✓	✓	✓	–	–	–
Bhudevi - FIRH	✓	✓	–	✓	✓	✓	✓
Somaskandar	✓	✓	–	✓	✓	–	✓
Pradoshamurthy	✓	✓	✓	✓	✓	✓	✓
Bhudevi	✓	–	✓	✓	–	✓	–

6. CONCLUSION

South Indian bronzes have been the focal point of attraction for many a researcher. A number of excellent treatises are available which dwell on the aesthetic beauty, casting traditions, composition, etc. However, while all these are individual and independent texts, this paper attempts to combine and highlight in a concise manner, the salient aspects of aesthetic beauty, technological excellence of the casting technology and characterization of bronzes through scientific investigations.

It can be observed from the above that most of the ancient science and technology of casting the icons was rather qualitative, empirical and adhoc with rather small amount of theoretical underpinning. None had thought of formulating a procedure and deriving the precise process sheet which could then be tested and implemented. As indicated by Dr. R.Nagaswamy in South Indian Bronzes [7] "The bronzes were part of sacred architecture, the living legacy of an unknown master artist who rendered these subtle and fluid forms as a means of expressing the divine. Made in accordance with codified principles, and sanctified by worship, these images were the link between Man and his God". Thus the main reason for the non formulation of procedures could be that in those times, to take things out of their normal context and to study them probably appeared to ancients as violating the religion. In the absence of these procedures of formulating and validating understanding i.e. the scientific method, it is very hard to make systematic progress and to discard or improve upon any particular practice. As Whitehead once said, "The essential discovery of modern science was the scientific method itself". It is the appreciation and practice of scientific method which in the modern context, is considered to lead to the progress of science. However, as can be observed from the above, the science and technology of South Indian bronzes is heuristic and empirical, but rigorous in practice. This approach made it possible to achieve consistency and excellence as revealed by the scientific investigations.

The developments in the field of science and technology are such that current artisans and the sthapatis must be in a position, to choose a certain copper alloy, whose properties are better than that of deployed compositions in ancient times, in terms of castability, polishing, casting without defects, lower melting point, etc. However, the scriptural commands of the *Agamas* would definitely prohibit the choice of these new alloys and the use of these icons (cast with an alloy other than the traditional bronze) for religious purposes. Yet, this is one direction which can lead to professional making of icons par excellence in the modern times.

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