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Investigation of Dhokra Casting in Light of Modern Engineering Technique

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Abstract

India is the goldmine of handicrafts. 'Dhokra' or 'Dokra' is a traditional metal casting art. It has enormous respect in both national and international markets. Dhokra is always considered art, whereas it is a technologically sound casting method. In the foundry world, it is famous as the 'investment casting process', 'near net shape casting processes', or 'lost wax casting process. The technical name of Dhokra is "wax-based investment casting in hot clay mold". Few tribal communities of eastern India (West Bengal, Chhattisgarh, Orissa, and Jharkhand) practice this technique. This 5000-year-old technology needs some development because only love and emotion are not enough to survive this technique. A planned technical analysis in light of modern engineering techniques is required to improve the quality and degree of excellence. Then only casting defects can be eradicated, and yielding and production costs can be minimized.

Keywords: *Dhokra Casting, Gating Calculation, Quality Analysis, Tribal Rural Casting*

1.0 Introduction

'Dokra' or 'Dhokra' is a sophisticated casting technique of rural India[1-4]. Impeccable and wonderful sculptures are made by Brass using this technique. The technique is almost 5000 years old[5], first discovered in the archeological sites of Indus valley civilization. The legacy is carried out by a small group of tribes. They lived in various parts of West Bengal, Chhattisgarh, Jharkhand and Orissa.

The casting technique is technically known as 'Wax based investment casting in hot clay mold'. Very thin-walled (500μm to 5000μm) hollow models, idols; utensils are produced in this practice. Liquid metal flow through such type of narrow region is a complex practice in foundry world.

Gating Design is very important for any type of casting. Gating system controls the liquid metal flow during mold filling. Due to the inappropriate gating design, either the mold will fill fast with a high-velocity liquid metal or the mold will fill slower. The high velocity of liquid metal causes mold damage, hence the surface quality degrades. The slow flow of liquid metal creates a solidification problem, which causes the defects like misrun, unfilled sections etc.

2.0 Field Visit

Some studies were done at Bikna, at Bankura district, in West Bengal. The production technique for a small candle stand was observed and the pictures at different stages were shown in Figure 1.

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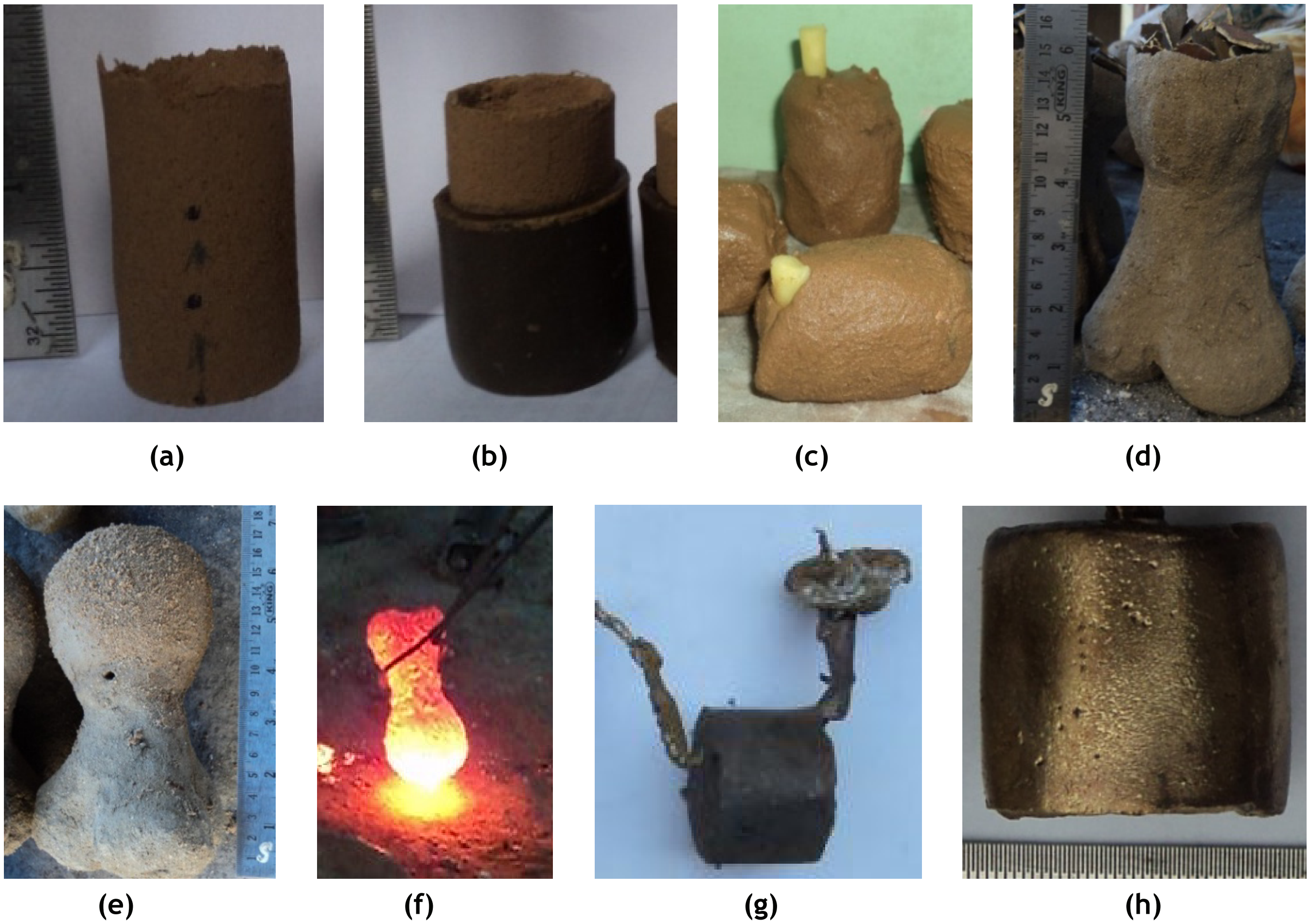


Figure 1. Steps of Production of Candle Stand: (a) Clay Core, (b) Wax Pattern, (c) Clay Mold (Primary Clay Coating), (d) Clay Mold (Secondary Clay) with cup; filled with brass scrap, (e) Covered clay mold, (f) Liquid metal Poured in Fired mold-pouring, (g) Cast product with gating system, (h) Cast Products.

3.0 Experimental Procedure

A Brass model of goddess "Saraswati" was cast by Dhokra casting technique. The steps of castings and the detailed dimension, part by part volume and area of the model was shown in Figure 2 and 3. The physical parameters of the casting and the gating details were tabulated in Table 1 and table 2 respectively.

Filling time and gating design calculation was determined and compared with actual one. Metallurgical and Mechanical analysis was done thereafter.

4.0 Result and Discussion

The filling time calculation and gating design calculation were shown below and the all the gating details and risering parameter and filling time were tabulated in Table 3, 4 and 5 respectively.

4.1 Filling Time Calculation

The conventional filling time cannot be used for thin walled castings. The Bernoulli's equation is traditionally used for calculate the mold filling time of top gating system. The liquid metal is not an ideal fluid which is an important assumption in Bernoulli's theorem. So, the filling time was calculated based on the following filling time equation derived elsewhere[6].

$$t_f = \frac{A_m}{A_f}\left[\frac{2}{\sqrt{g}}\left(\sqrt{k} - \sqrt{k - Z_m}\right) + \frac{2b}{g}\ln\left(\frac{\sqrt{k} - \frac{b}{\sqrt{g}}}{\sqrt{k - Z_m} - \frac{b}{\sqrt{g}}}\right)\right] \qquad (1)$$

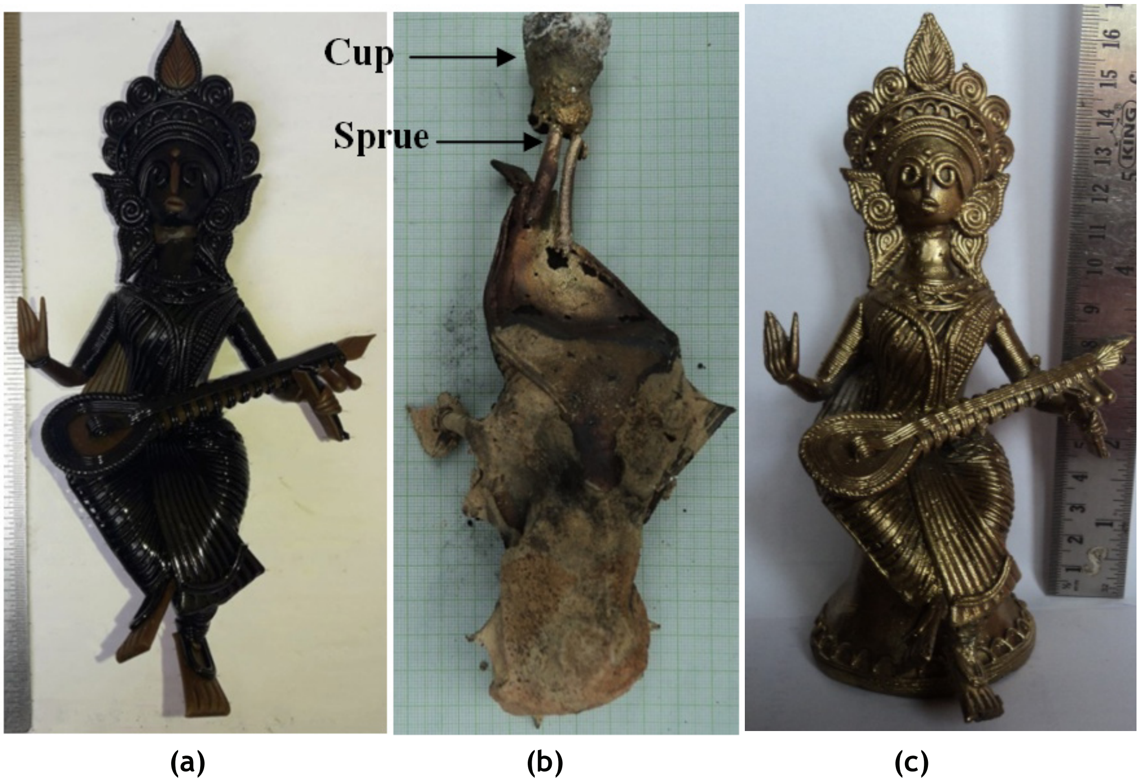


Figure 2. . (a) Wax Patten, (b) casting with gating system, (c) Finished Model.

- Assumptions:

Top gating, Discharge coefficient, C_D = 0.8[7], For 60-40 Brass: Viscosity (μ), mPa.s = 4[8], And Density (ρ), kg/m^3 = 8400[9], surface energy (γ), mN/m = 2000[10], contact angle (θ), rad = 2.37[11]. z_s, m = (Sprue + cup Height) = (0.04+0.03), Path traveled by liquid metal: L_m, m = 185 mm, hydraulic diameter: d_H, m=2w=0.002. Mold Temperature is more than 1000^{0}C and liquid metal temperature 950^{0}C.

- Velocity entered into the cavity (at gate):

$$v_g = C_D\sqrt{gz_s}$$
$$= 0.8\sqrt{9.81\times(0.04+0.03)} = 0.868 m/s \quad (2)$$

- Effect of resistance due to surface tension [γ = 2 N/m, θ = 135.79^0, w = 1.0mm]
- $\Delta P_\gamma = -\dfrac{2\gamma}{w}\cos\theta$
- $$= -\frac{2\times2\times10^{-3}}{0.001}\cos(135.79) = 2867 N/m^2 \quad (3)$$
- Calculation of Constants:

$$b = \frac{24\mu L_m}{\rho d_H^2} = 0.53 \quad (4)$$

$$k = \frac{1}{g}[b^2 + gz_m + v_g{}^2 - \frac{\Delta P_\gamma}{\rho_{liq}}] = 0.26 \quad (5)$$

- Flow area: Number of Sprue (n) = 2; and as, Gate diameter (d_g) less than Thickness (w), therefore

$$A_f = n\times d_g\times w \quad (6)$$

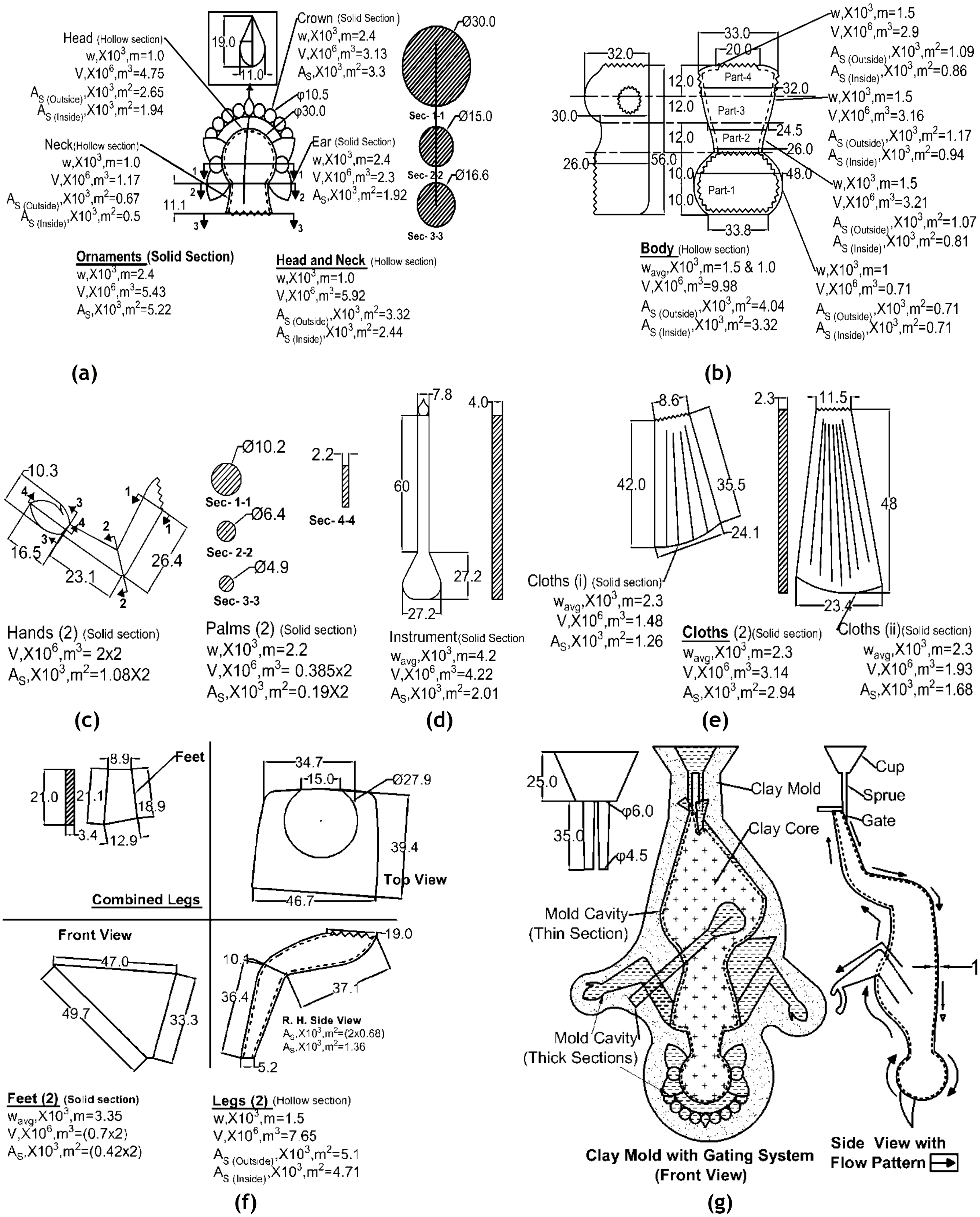
$$\Rightarrow 2\times0.004\times0.001 = 8\times10^{-6} m^2$$

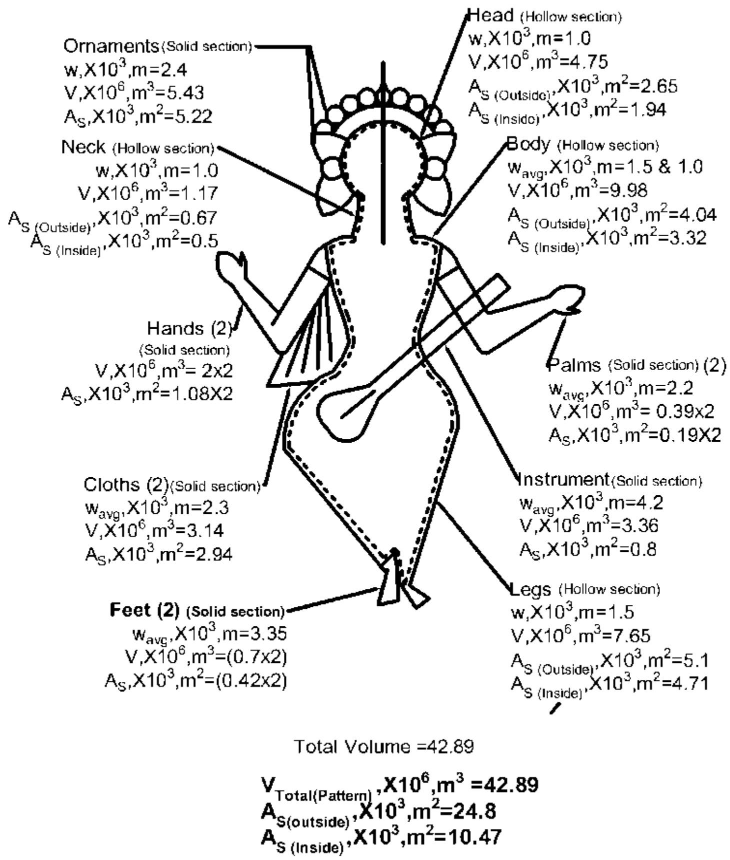
- Average Mold Area:

$$A_m = \frac{Casting\ Volume(V)^2}{Mold\ Height(Z_m)} \quad (7)$$

$$= \frac{42.9\times10^{-6}}{157\times10^{-3}} = 0.273\times10^{-3} m$$

- Calculated Filling Time: t_f = 7.14 second
- Actual Filling time was 7.6 second.
- Error Calculation :


Head (Hollow section)
w,X10³,m=1.0
V,X10⁶,m³=4.75
A_S (Outside),X10³,m²=2.65
A_S (Inside),X10³,m²=1.94
Crown (Solid Section)
w,X10³,m=2.4
V,X10⁶,m³=3.13
A_S,X10³,m²=3.3
Neck (Hollow section)
w,X10³,m=1.0
V,X10⁶,m³=1.17
A_S (Outside),X10³,m²=0.67
A_S (Inside),X10³,m²=0.5
Ear (Solid Section)
w,X10³,m=2.4
V,X10⁶,m³=2.3
A_S,X10³,m²=1.92
Ornaments (Solid Section)
w,X10³,m=2.4
V,X10⁶,m³=5.43
A_S,X10³,m²=5.22
Head and Neck (Hollow section)
w,X10³,m=1.0
V,X10⁶,m³=5.92
A_S (Outside),X10³,m²=3.32
A_S (Inside),X10³,m²=2.44
(a)
Part-4
Part-3
Part-2
Part-1
w,X10³,m=1.5
V,X10⁶,m³=2.9
A_S (Outside),X10³,m²=1.09
A_S (Inside),X10³,m²=0.86
w,X10³,m=1.5
V,X10⁶,m³=3.16
A_S (Outside),X10³,m²=1.17
A_S (Inside),X10³,m²=0.94
w,X10³,m=1.5
V,X10⁶,m³=3.21
A_S (Outside),X10³,m²=1.07
A_S (Inside),X10³,m²=0.81
Body (Hollow section)
w_avg,X10³,m=1.5 & 1.0
V,X10⁶,m³=9.98
A_S (Outside),X10³,m²=4.04
A_S (Inside),X10³,m²=3.32
w,X10³,m=1
V,X10⁶,m³=0.71
A_S (Outside),X10³,m²=0.71
A_S (Inside),X10³,m²=0.71
(b)
Hands (2) (Solid section)
V,X10⁶,m³= 2x2
A_S,X10³,m²=1.08X2
Palms (2) (Solid section)
w,X10³,m=2.2
V,X10⁶,m³= 0.385x2
A_S,X10³,m²=0.19X2
(c)
Instrument (Solid Section
w_avg,X10³,m=4.2
V,X10⁶,m³=4.22
A_S,X10³,m²=2.01
(d)
Cloths (i) (Solid section)
w_avg,X10³,m=2.3
V,X10⁶,m³=1.48
A_S,X10³,m²=1.26
Cloths (2)(Solid section)
w_avg,X10³,m=2.3
V,X10⁶,m³=3.14
A_S,X10³,m²=2.94
Cloths (ii)(Solid section)
w_avg,X10³,m=2.3
V,X10⁶,m³=1.93
A_S,X10³,m²=1.68
(e)
Feet
Combined Legs
Top View
Front View
R. H. Side View
A_S,X10³,m²=(2x0.68)
A_S,X10³,m²=1.36
Feet (2) (Solid section)
w_avg,X10³,m=3.35
V,X10⁶,m³=(0.7x2)
A_S,X10³,m²=(0.42x2)
Legs (2) (Hollow section)
w,X10³,m=1.5
V,X10⁶,m³=7.65
A_S (Outside),X10³,m²=5.1
A_S (Inside),X10³,m²=4.71
(f)
Clay Mold
Clay Core
Mold Cavity (Thin Section)
Mold Cavity (Thick Sections)
Cup
Sprue
Gate
Clay Mold with Gating System (Front View)
Side View with Flow Pattern
(g)



(h)

Figure 3. Schematic diagram of (a) head, neck and ornaments, (b) body, (c) hand, (d) music instrument, (e) cloths, (f) legs and feet, (g) clay mold with gating system and liquid metal flow direction, (h) overall schematic diagram of the model with volume, inside and outside surface area.

$$\boldsymbol{Error} = \left(\frac{t_{actual} - t_{calculated}}{t_{actual}}\right) \times 100\% \tag{8}$$

$$= \left(\frac{7.6 - 7.14}{7.6}\right) \times 100\% = 6.05\%$$

- Checking with Reynold's no.
-

$$Re = \frac{\rho v d}{\mu} = \frac{8400 \times 0.868 \times 0.001}{0.004} = 1822.5 \tag{9}$$

4.2. Gating Design

The calculated data of gating details, Risering Parameter and filling time were tabulated in Table 3, 4 and 5 respectively. Gating design given in Brass castings were calculated as follows.

- Sprue Design: Cup Diameter, dc, m; Gate Diameter, dg, m; Cup Height, z_c, m; Total Sprue Height, z_t, m Aspiration Correction,

$$\frac{d_g}{d_c} = \sqrt[4]{\frac{z_c}{z_t}} \Rightarrow \frac{4.5}{d_c} = \sqrt[4]{\frac{25}{60}} \Rightarrow d_c = 5.6mm \tag{10}$$

Actual Cup Diameter, dc= 2 × 6 mm

- Riser Design: Riser diameter, d_r, m; Modulus of the casting, M_c,

$$M_C = \left(\frac{Vol}{Area}\right)_{Casting} = \left(\frac{42.89\times10^{-6}}{35.27\times10^{-3}}\right) = 1.216\times10^{-3} \tag{11}$$

Modulus of Riser, M_r, m;

$$M_r = 1.1 \times M_c \tag{12}$$

Assume, Cylindrical Riser, $d_r = h_r$ so,

$$M_r = \frac{d_r}{4} \Rightarrow d_r = 4.87mm \tag{13}$$

Actual Riser Diameter (Sprue act as Riser):

$$d_c = 2 \times 4.5 = 9 \text{ mm} \tag{14}$$

Table 1. Physical Parameters of The Casting

Description	Symbol, unit	Value
Weight of Casting	$W_{Casting}$, $x10^3$, kg	360
Vol. of Casting	$V_{Casting}$, $x10^6$, m^3	42.89
Outside Area of Cast	$A_{outside}$ $x10^3$, m^2	24.8
Inside area of cast	A_{inside} $x10^3$, m^2	10.47
Total Heat dissipating Area	A_{Total} $x10^3$, m^2	35.27
Height	z_m x 10^3, m	157
Path length of Flow	L_m, x 10^3, m	185
Avg. Width	w_{avg}, x 10^3, m	1.5
Effective Width	$w_{Effective}$, x 10^3, m	1

Table 2. Gating Details

Description	Symbol, unit	Value
Number of Sprue	n	2
Gate Diameter	d_g, $\times 10^3$, m	4.5
Sprue Height	z_s , $\times 10^3$, m	3.5
Cup diameter	d_c, $x10^3$, m	6
Cup Height	z_c, $x10^3$, m	25
Gating Vol.	V_{Gating}, $\times 10^6$, m^3	5.16
Gating Surface Area	A_{Gating}, $\times 10^3$, m^2	2.21

- Hot metal required (W_{Req}): [considering, 20% extra metal for drossing and spilling]

$$W_{Req} = (V_{Casting} + V_{Gating}) \ x \ \rho_{Brass\ (Liquid)}, \text{kg} \tag{15}$$

- Yield of the Casting:

$$\boldsymbol{Yield} = \frac{\boldsymbol{W_{Casting}}}{\boldsymbol{W_{Required}}} \cdot \mathbf{100}\ (\%) \tag{16}$$

4.3 Metallurgical Analysis

Microstructure of investment castings already designed for gating and Risering are presented in figure 3 and the SEM (scanning electron microscope) microstructure along with EDX (energy dispersive X-ray spectroscopy) analysis is shown in Figure 4. All the microstructures[12] are 60/40 Brass containing very coarse grains of dendrites for α – Copper phase surrounded by Zinc rich β-phase. Chemical compositions with the bulk and micro hardness are presented in Table 5. Zn equivalent[13] was also mentioned in the Table 5.

4.4 Surface Roughness Analysis

Surface roughness is one of most satisfactory parameter to judge a product quality[14,15]. The surface roughness was measured (Figure 5), following "ISO standards ISO 5436-2:2012"[16]. The best and worst Ra (Arithmetic mean of departures) and Rq (Root mean square of the surface roughness) values are given here:

Table 3. Risering Parameter

Description	Symbol, unit	Value
Calculated Cup Diameter	d_c, x10^3, m	5.6
Calculated Riser Diameter	d_R, x10^3, m	5.36
Hot metal required	W_{Req}, kg	0.484
Yield	%	74.4
$(V/A)_{Casting}$		1.22×10^{-3}
$(V/A)_{Gating}$		2.33×10^{-3}

Table 4. Filling Time

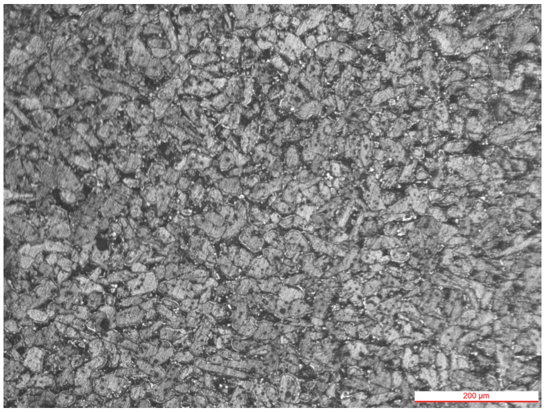
Description	Symbol, unit	Value
Gate Vel	v_g, ms^{-1}	0.86
Avg. Cross-sectional Mold Area	A_m, x10^3, m^2	0.273
Flow Area	A_f x10^6, m^2	9.0
Calculated Filling Time	t_f, sec	7.14
Actual Filling Time	t_{actual}, sec	7.6
Error	%	6.05
Reynolds no.		1822

Table 5. Chemical composition and hardness of cast metal

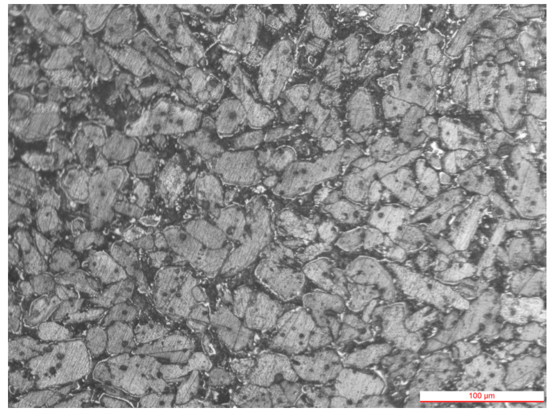
Cu (%)	Zn (%)	Pb (%)	Fe (%)	Sn (%)	others	Zn Equivalent	Cu : Zn Ratio
60.6	33.86	2.8	0.9	0.79	1.05	38.4	61.6 : 38.4
Bulk Hardness (HV 5/10)				Micro Hardness [α-Cu Phase] (HV 50/10)			
109.2				114.2			

Best Surface Ra = 1.48 μm, Rq = 1.7 μm; worst surface: Ra = 3.41 μm, Rq = 3.87 μm

Figure 1, (200X) (Etchant: $FeCl_3$ in HCl) All compositions are given above in wt.%. The coarse microstructure of the icon has been depicted in the SEM photograph. The structure is single phase of α-Cu-Zn-Sn-Pb solid solution with very little β-phase (black colored) within it. Dendrites are very coarse indicating very slow rate of solidification. The round phases are insoluble lead constituents. The compositions of matrix α-phase (Cu-rich) and minor β-phase (solute rich) in the interdendritic region has been marked.



Magnification:100X



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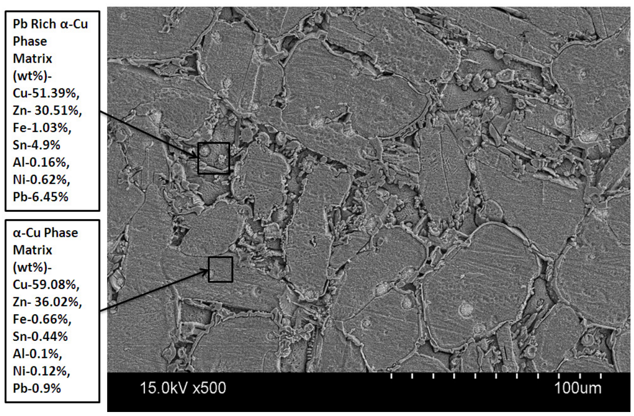
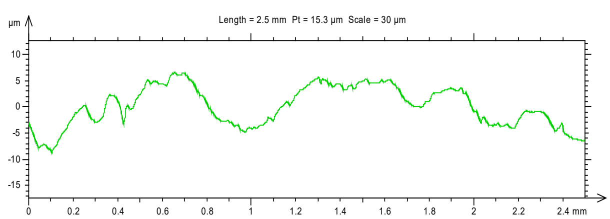
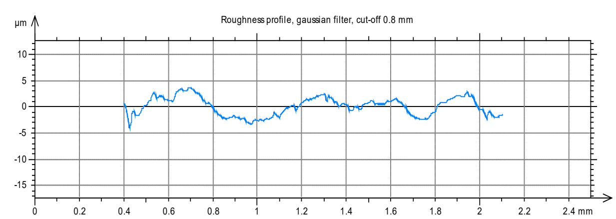


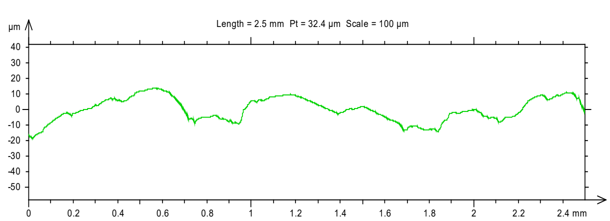
Figure 4. [Etchant: Fecl3 in HCL] Microstructure of Investment Casting. Developed in this design shows α – Cu phase dendrites as matrix surrounded by β – phase. All the grains are coarse in nature indicating slow rate of cooling in hot molds.



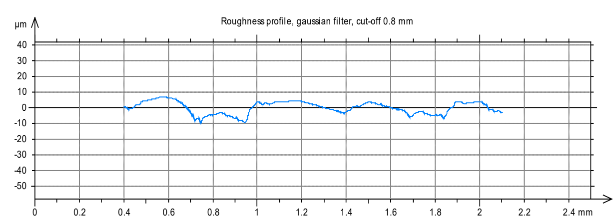
Surface Profile of Best Surface



Roughness profile of Best Surface



Surface Profile of Worst Surface



Roughness profile of Worst Surface

Figure 5. Surface Profile and Roughness profile of the best (top) and worst surface (bottom). Sample length 2.5 mm, scale= 100µm, filter used: Gaussian, cut off: 0.8mm

5.0 Conclusion

The scope of work may be extending to engineering component over the artistic product, if this process is cost effective. This project is just the first step of new beginning.

- The simulated gating and riser design for thin walled investment castings can guide us in reconstructing the methoding technique adopted by ancient casters.
- The metallurgical investigation can very well rewrite the casting alloys and the molding systems utilized by different metal cultures in India. This may unfold new information about the state of the art of that period which would be helpful to understand the development of human activity with available facility at that period.
- Surface roughness of the worst part of the casting implies the efficacy of the technique because the model was polished a little bit after casting.
- The ancient technique even satisfactory enough even under the modern day's technology based investigation.

6.0 Acknowledgment

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7.0 References

1. Mandal B, Chattopadhyay P, Datta PK. Characterization of a Pala-Sena, High-Tin Bronze Bowl from Bengal, India. Society for Archaeological Sciences, (SAS) Bulletin, University of South Florida, USA. (2008); pp. 12-17. https://socarchsci.org/images/bulletin/SAS3103.pdf
2. Mandal B, Datta PK. Hot mold casting process of ancient East India and Bangladesh. China Foundry. 2010; 7(2):171-7.
3. Mandal B, Datta PK. Understanding Alloy Design Principles and Cast Metal Technology. In Hot Molds for Medieval Bengal. Indian J Hist Sci. 2010; 45(1):101-40. https://insa.nic.in/writereaddata/UpLoadedFiles/IJHS/Vol45_1_5_BMandalarticle.pdf
4. Craddock PT. The Metal Casting Traditions of South Asia: Continuity and Innovation. Indian J Hist Sci. 2015; 50(1):55-82. https://doi.org/10.16943/ijhs/2015/v50i1/48112
5. Chattopadhyay PK. Archaeometallurgy in India: Studies on Technoculture in early Copper and Iron Ages in Bihar, Jharkhand and West Bengal. K.P. Jayaswal Research Institute, Patna, 2004.
6. Roy S, Pramanick AK, Datta PK. Precise filling time calculation of thin-walled investment casting in hot mold. J Braz Soc Mech Sci Eng. 2020; 42:552. https://doi.org/10.1007/s40430-020-02634-6
7. Campbell J. Campbell-10 Rules. Elsevier. 2004; pp. 28-9. https://doi.org/10.1177/089202069601000412
8. Assael MJ, et al. Reference data for the density and viscosity of liquid cadmium…. mercury. J Phys Chem Ref Data. 2012; 41(3):033101-1-033101-16. https://doi.org/10.1063/1.4729873
9. Gupta SV. Practical density measurement and hydrometry. IoP. 2002; pp. 123. https://doi.org/10.1201/9780367801496
10. Nakayama Y. Introduction to fluid mechanics. Butterworth, Oxford. 1999; pp. 13.
11. Nakayama, Boucher RF. Introduction to Fluid Mechanics, Butterworth, Heinemann.
12. Donga YW, Lia XL, Zhaoa Qi, Yangc Jun, Dao Ming. Modeling of shrinkage during investment casting of thin-walled hollow turbine blades. Journal of Materials Processing Technology. 2017; 244:190-203. https://doi.org/10.1016/j.jmatprotec.2017.01.005
13. Rollason EC. Metallurgy for Engineers. ELBS, UK 1977; pp. 310.
14. Roy S, Pramanick AK, Datta PK. Quality Analysis of Tribal Casting Products by TOPSIS for Different Gating System. IOP Conf. Series: Materials Science and Engineering. 2021; 1080:1-5. https://doi.org/10.1088/1757-899X/1080/1/012014
15. Roy S, Pramanick AK, Datta PK. The Effect of Gating System on Quality of Traditional Rural Metal Castings of India, Recent Trends in Industrial and Production Engineering. Lecture Notes in Mechanical Engineering, Springer Nature. https://doi.org/10.1007/978-981-16-3135-1_27
16. Geometrical product specifications (GPS)-surface texture: Profile method. Measurement standards - part 2: software measurement standards. https://www.iso.org/standard/61261.html

Nomenclature

	Sym.	Meaning (unit)		Sym.	Meaning (unit)
1.	V	Casting Volume	14.	ρ	Density (kg/m^3)
2.	z_s	Sprue height (m)	15.	μ	Viscosity (m.Pa.s)
3.	z_m	Mold height (m)	16.	$\boldsymbol{\gamma}$	surface energy (N/m)
4.	z_c	Cup dia (m)	17.	$\boldsymbol{\theta}$	contact angle (^{0})
5.	w	Width of mold (m)	18.	d_r	Riset diameter (m)
6.	v_g	Velocity at gate (m/s)	19.	d_H	Hydraulic diameter (m)
7.	d_g	Gate diameter (m)	20.	Re	Reynolds No
8.	t_f	Filling time (s)	21.	$b.k$	Constants
9.	A_m	Cross-sectional area of mold (m^2)	22.	A_g	Cross-sectional area of gate (m^2)
10	A_f	Area of flow inside mold (m^2)	23.	M_r	Modulus of the Riser (m)
11	L_m	Length of liquid metal flow path passes through mold (m)	24.	g	Gravitational accelaration (m/s^2)
12.	$\boldsymbol{\alpha}$	Kinetic Energy Correction Factor ($\boldsymbol{\alpha} = 2$)	25.	z_f	Friction Head Loss (m)
13.	M_c	Modulus of the Casting (m)	26.	C_D	Discharge Co-efficient