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Negative Shrinkage of Thin-walled Investment Brass Castings

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Abstract

'Dhokra' or 'Dokra' casting is a sophisticated cast metal craft tradition of the Indian subcontinent. It has been practiced by the countryfolk now since the Copper Age. It is a lost wax casting process in the hot clay mold. The technology is such sophisticated that it can produce up to 400 µm thin-walled hollow cast products with complicated and intricate shapes using Brass, Bronze, Copper, and other copper alloys. The investigation was for engraving Brass (2% lead) which is used by Dhokra artisans nowadays. In a field visit during dimensional analysis, one discrepancy was identified. The metal thicknesses of hollow castings are thicker than the thickness of the wax pattern. This cast metal dilation phenomenon is unusual. Shrinkage of metals compared to the pattern dimension is familiar in the casting world. The same abnormalities in the repeated investigation at different sites were observed. All the studies and experiments were organized to explain the reason hidden behind the phenomenon.

Keywords: 'Dokra' or 'Dhokra', Investment casting, Thin-walled casting, Clay Mold, Cast metal dilation

1. Introduction

The Indian Dhokra artisans practiced the casting technique from ancient times (since 5000 years approximately) [1-2]. In the present time, this process is known as lost wax investment casting in hot clay mold or near net shape casting processes [3-11]. Thin-walled hollow complex-shaped castings are the majority of their product. Even less than 500µm thin-walled castings are cast. The products are ready to packaging with very nominal finishing or machining operation. Despite not using modern instruments, the rejection rate is negligible [12].

There are several stages to produce a 'Dhokra' item beginning with making a clay core for hollow casting. Then the wax pattern (wax sheets and thread) is stuck on the clay core using heat. The wax patterns are prepared at the beginning without any clay core for solid castings. The thickness of wax sheets and wax threads may be thicker than 4 mm and sometimes thinner than 0.5 mm. After that, the mixture of clay, sand, rice husk, cow dung, and other ingredients is pasted layer by layer over a wax pattern. After drying the mold, it was inserted into the furnace and liquid metal was poured at the red-hot condition of the mold.

An interesting finding was investigated during the dimensional analysis of 'Dokra casting'. The thickness of the cast metal is expanded compared to the wax pattern; which is an exceptional case. Generally in the casting world during pattern making shrinkage allowance is taken into account as metal always shrinks compared to pattern dimension [13] during solidification. In this project, only solid parts of the castings were investigated for easy understanding. Theoretical analysis, as well as experimental analysis, was carried out to identify the reason(s) behind this unusual phenomenon.

2. Understanding the problem

The problem was first identified during the visit to a famous 'Dhokra' centre [14] at Bikna Shilpa Danga, Bankura District, West

Bengal, India (23°15.3"N 87°5.9"E) and then the same phenomenon was found during a field visit at Dariapur, District Burdwan of West Bengal, India (23°29'1"N 87°44'6''E).

As the focus of the work was concentrated on solid parts of the castings or solid castings, so the production technique of solid casting is discussed here. Also, analysis of the metal used for casting was studied for a better understanding of the problem.

2.1. Production Technique

A model of a peacock (figure-1) was designed in such a way that most of the parts were solid sections. The elaborated process was described in tabulated form (figure-1).

Various materials like silica sand, cow dung, rice husk etc. are mixed with local Kaolinite clay at different ratios for mold making (table-1). Several types of a mixture of Bee's wax and other components (table-2) are prepared for making different parts of the wax pattern.

2.2. Analysis of the Metal used for casting

Chemical analysis, bulk and micro hardness, and SEM-microstructure of the cast metal were investigated to identify the metal used for casting.

Chemical Analyses of cast metals had been done by Spectroscopy using the standard- IS 4027. The bulk hardness of the cast samples was measured by the Vickers Hardness testing machine (model no. VM 50, Sr. No. 02/2006– 815) and the micro-hardness of the relevant phases from the microstructures was measured by the Micro hardness tester (model: LEICA-VMHT, Serial No. 518880). The scanning electron microscopy of specimens was done by Oxford, JEOL JSM-6360.

2.2.1 Chemical analysis and hardness

Chemical analysis (table-3) of the cast metal shows that the metal used for regular casting is Engraving Brass (2% lead) having UNS No. C35600 and ISO No.: CuZn39Pb2 (table-4) [15-16]. Calculated Zinc equivalent [17] is also determined.

Bulk hardness and Micro Hardness of the α-Cu Phase of the cast metal samples for different thicknesses were measured and tabulated in table-3.

2.2.2. Microstructure

Microstructures of thin and thick sections of thickness 1.0 mm and 3.0 mm respectively were studied using a scanning electron microscope (SEM). The microstructure (figure-4) of the Brass sample exposes the visible dendrites with well-marked grain boundaries. The dendrites of the cast metal consist of the α-Cu phase (grey coloured) as the major phase. From the analysis of the microstructure, it was observed that the grain size increases with the increase in thickness of the casing.

2.3. Shrinkage Analysis of Metal Thickness

The thicknesses of wax sheets and threads were measured during pattern-making at various positions of that sample. After casting the metal thicknesses were measured for the same positions. The metal thickness shrinkage percentage was calculated followed by the given formula [18]

$$\textbf{Metal Thickness Shrinkage} = \left[\frac{t_W - t_M}{t_W}\right] \times 100\% \qquad (1)$$

Where, t_W = thickness of wax pattern, t_M = thickness of cast metal thickness. Conventionally this formula is used to measure the shrinkage percentage of metal compared to the pattern and the shrinkage is considered as positive (+ve) which is used as 'Shrinkage Allowance' during pattern design. That is why here shrinkage is considered as positive quantity and expansion as negative quantity. The distribution of metal thickness compared with wax pattern thickness is shown in figure-3 and the shrinkage/ expansion percentage was tabulated in table-5. It was clearly noticed that the metal thicknesses had negative shrinkage (i.e. expansion or dilation) compared to the wax pattern [19].

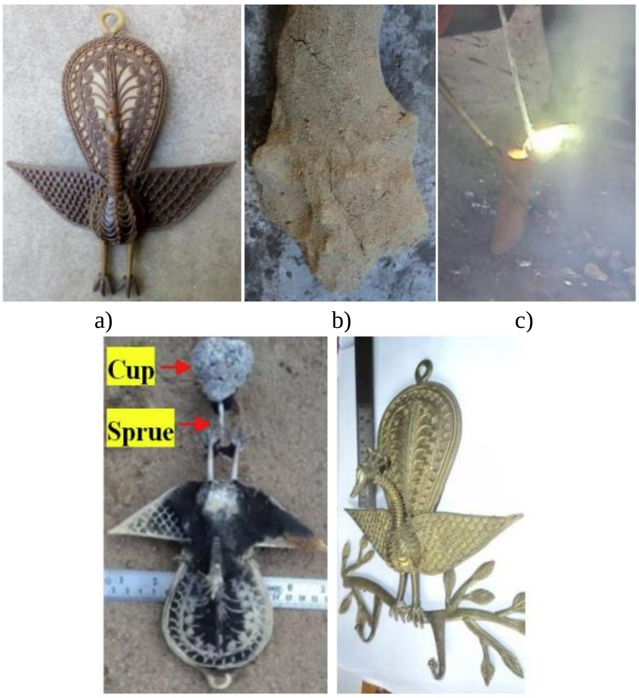


Fig. 1. The production stages of model Peacock: (a) Wax Pattern, (b) Clay mold over the wax pattern, (c) liquid metal poured into the hot mold (d) Unfinished model with gating system, (c) Final product

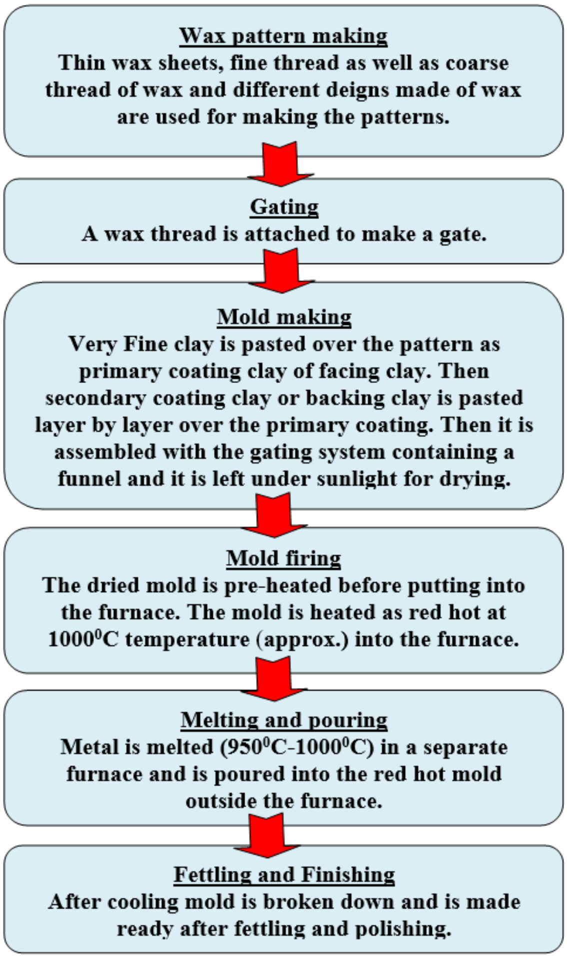


Fig. 2. Production stages of investment casting

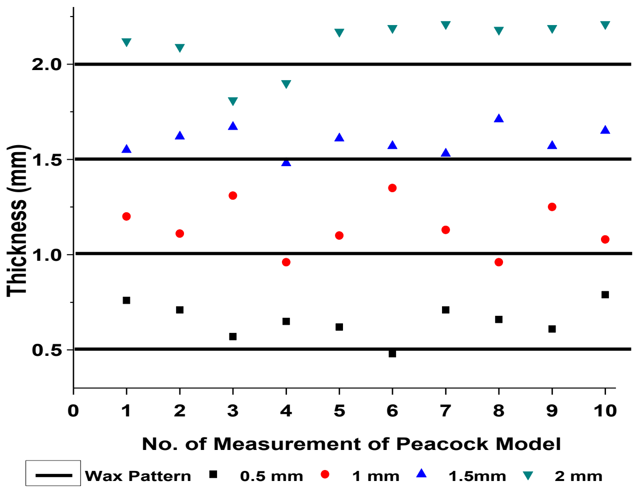


Fig. 3. Distribution of Metal Thickness compare for different Wax Pattern thickness, Negative shrinkage is noticeable

Table 1.
Materials used for pattern

	Mixture- 1	Mixture- 2	Mixture- 3
Materials Used	Petroleum tar (Pitch) (65%) + Sal Dammar resin (35%)	Sal Dammar resin (40%) + Bees wax (60%)	Sal Dammar resin (40%) + Bees wax (20%) + Paraffin wax (40%)
Used For	Thin sheet of wax	Making solid extended section, like legs, hands	Making threads, complicated designs

Table 2.
Materials used for mold

Clay and Sand type	Components	Analysis
Clay	Local Kaolinite Clay	3Al2O32SiO22H2O or Al2Si2O5(OH)4
Sand	Silica Sand	SiO2
Primary Coating (Facing clay)	Very fine Kaolinite (100%)	GFN=125; pH=7.2 Base Exchange Capacity= 0.37
Secondary Coating (Backing clay)	Kaolinite (20%-30%) + Rice husk + Cow Dung + Jute Cuttings (10%) + Fine and Medium Silica Sand (60%-70%)	GFN=61; pH=7.87 Base Exchange Capacity= 1.7

Table 3.
Chemical composition and hardness of cast metal

Cu %	Zn%	Pb%	Fe%	Sn%	Zn Equivalent	$\frac{Cu}{Zn}$ Ratio
60.6	33.86	2.85	0.92	0.77	38.41	$\frac{61.59}{38.41}$
Section or thickness					Thin (1mm)	Thick (3mm)
Bulk Hardness (HV 5/10)					108.0	92.2
Micro Hardness [α-Cu Phase](HV 50/10)					114.2	88.5

Table 4.
Nomenclature and property of metal

Common Name: Engraving brass (2% lead)	Cu%:59.0-64, Zn%: ~ 39, Pb%: 2.0-3.0
UNS NO.- C35600;	ISO No.: CuZn39Pb2
AS NO.- 356	JIS No.: C3560
Melting point:885°C	Thermal expansion co-efficient 20.5 µm/m°C (within the range of 20°C - 300°C)

Table 5.
Cast metal thickness Expanion (-ve shrinkage)

Wax Pattern Thickness (mm)	$0.5^{+0.05}_{-0.05}$	$1.0^{+0.1}_{-0.1}$	$1.5^{+0.1}_{-0.1}$	$2.0^{+0.1}_{-0.1}$
Avg. Metal Thickness (mm)	0.65	1.14	1.59	2.1
Avg. Expansion (%)	-31.2	-14.5	-6.4	-5.35

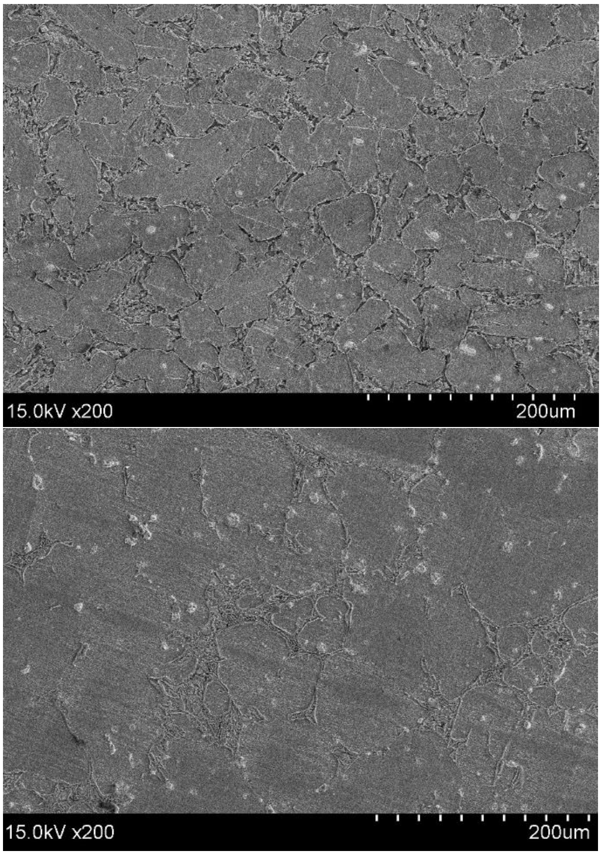


Fig. 4. SEM Microstructure (200X) of Thinner section (1mm) (top) and thicker section (3mm) (bottom). Etchant: $FeCl_3$ in HCl. The single - α-Cu phase with inter dendritic region solute rich β-Cu phase is present. Distributed lead (Pb) is everywhere

2.4. Theoretical aspects

The dilation of cast metal sheets compared to wax patterns is quite an unusual phenomenon. To explain the phenomenon the study of the ingredient of clay mold material is required.

The presence of Kaolinite and Silica Sand was found in the clay mixtures used for making the mold. Generally, the presence of Kaolinite clay is almost everywhere at Bankura, where the Dhokra site is situated [20-22]. The study on Kaolinite clay [23] on changes in length from room temperature to 1000^{0}C was explored by Hyslop, McMurdo (1938) [24] and Heindl and Meng (1939) [25] by using differential thermal expansion apparatus and interferometer respectively.

One of the most important ingredients of mold materials is silica sand. It is already mentioned in table-2 that fine and medium Silica sand is present (60%-70%) in the exterior coating of the mold which actually takes 95% of the total mold. According to J. Thiel [26], Silica sand expands by approximately 4.74% to 12.44 by volume at different temperature ranges. The details of the expansion and contraction of Kaolinite clay and Silica sand along with an explanation are documented in table-8.

The research of the scientists illustrates that Kaolinite clay contracts and Silica sand expand at a high-temperature range. Clay molded investment casting involves both the ingredients in a certain percentage for different stages, so, it is essential to estimate the shrinkage and expansion nature of clay mold separately.

Table 6.
Transformation details of kaolinite clay and silica sand

	Temperature (^{0}C)	Expansion/ Contraction by volume (%)	Explanation
Kaolinite Clay	470^{0}C – 550^{0}C	0.3% Expansion	---
	550^{0}C - 650^{0}C	1.0–1.8 % Contraction	Dehydroxylation
	650^{0}C – 920^{0}C	1.5–2.3 % Contraction	Escape of OH groups as water/steam
	930^{0}C – 980^{0}C	1.0–1.4 %.Contraction	Formation of Mullite (mullitization)
	Above 1000^{0}C	Contraction	Formation of a molten phase
Silica Sand	573^{0}C	4.74% Expansion	Alpha-quartz to beta-quartz
	870^{0}C	12.44% Expansion	Beta-quartz to beta-tridymite
	1470^{0}C	2.27% Expansion	Beta-tridymite to beta-cristobalite
		14.71% Expansion	Beta-quartz to beta-cristobalite

3. Experimental Procedure

The experiment was designed to understand the nature of shrinkage or expansion of the Cast metal as well as mold materials. All the dimensions were measured followed by the ISO standard-ISO 1:2016 [27].

3.1. Shrinkage Analysis of Mold Material

The experiment was designed to understand the shrinkage or expansion behavior of clay mold during heating.

A few solid cylinders of the same size and shape were made using the mold materials (i) facing-clay (primary clay) and (ii) backing-clay (secondary clay). The dimensions and weights were measured after getting completely dry. The samples were heated at 1000^0C (figure-5). The temperature for the experiment was chosen based on the data from the field visit.

3.2. Shrinkage Analysis of Cast Metal

The experiment was designed to cast five different thicknesses of sheets of 0.5mm, 1mm, 1.75mm 2.5mm, and 3.25mm. The production steps of the sheets were elaborated on in figure -6.

The wax thickness of the patterns and metal thickness of the castings were measured at similar positions and then shrinkage or expansion was determined.

4. Results and Discussion

The experimental results for shrinkage analysis of mould material and metal casting have been discussed.

4.1. Experimentation of mold material

The result shows (table-7) that both the radial and the longitudinal dimensions of all molding materials had expanded. The weight of the dried clay at room temperature and the fired clay samples along with the loss of weight percentage has shown in table-5.

4.2. Reason behind the expansion of mold material

The explanations for the expansion of mold materials are as follows:

- Silica generally expands by 4.74% to 12.4% by volume (table-6) at the temperature of 573^0C and 870^0C respectively. The amount of shrinkage of Kaolinite at different temperature zone is very low (maximum 1.8%) compared to silica sand.
- The shrinkage or expansion of the mold is mostly controlled by the Silica Sand because of its adequacy (60%-70%) in the clay mold, especially in secondary coating clay (backing clay mold) which occupies 95%-98% of the total mold.
- The thickness of Primary coating clay (Facing clay) over the wax pattern is not used more than 1.0 mm in regular practice. Whereas the secondary coating clay (backing clay) is 20 to 50 times thicker than facing clay based on the volume of casting. So, the primary layer has a negligible effect on the shrinkage or expansion of the mold.
- Secondary mold clay expanded at all temperatures compared to others, which signifies that the volume of mold cavity increases for the investment casting in the hot clay mold.

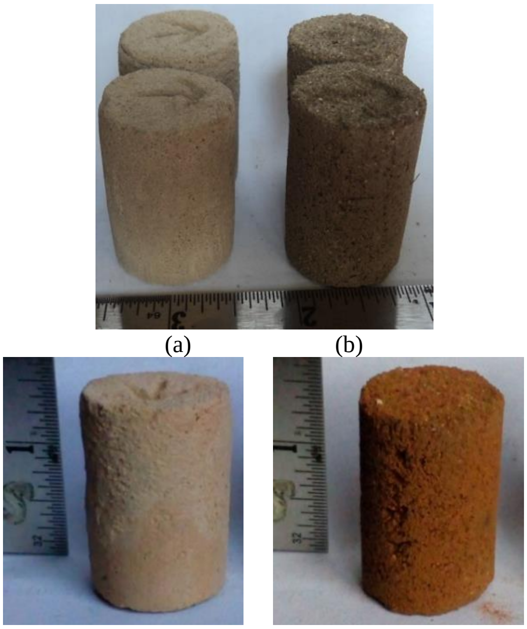
4.3. Shrinkage analysis of cast metal thickness

The dimensional distributions of the thicknesses of cast metal parts were shown in figure-7 and the expansion percentage (compared to wax pattern thickness) was shown in table-8. It was observed that the amount of dilation cast metal thicknesses decreases with the increase in metal thickness.

4.4. Reason behind the expansion of cast metal

The reasons behind the expansion of cast metals are follows:

- In previous experiment, it was proven that the volume of mold cavity increases for the investment casting specially at high temperature and liquid metal is poured at that condition. So, liquid metal has more space than the wax pattern thickness.
- To understand the mechanism, the stages of heating and cooling sequence of clay mold was shown in table-9, based on the experimental and theoretical analysis [28-29].
- Metal thickness expansion percentage getting gradually decrease with the increase in thickness. Mold thicknesses are usually same for all the sections. So, the expansion of mold was approximately the same at every point. But on another side solid-solid contraction is more for thicker sections. So, the thicker sections can overcome the mold cavity dilation phenomenon more than thinner sections.

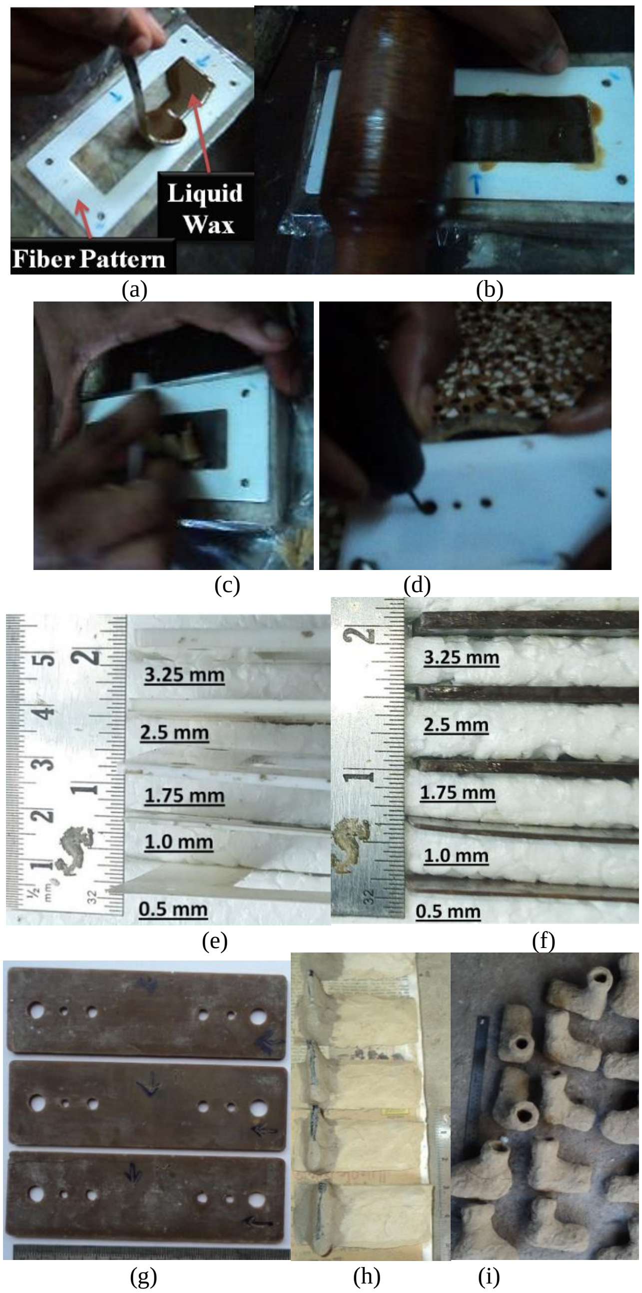


(a) (b) (c) (d)

Fig. 5. Experiment to estimate the shrinkage and expansion of mold material. At room temperature: (a) Primary clay, (b) Secondary clay; At 1000^0C: (c)Primary clay, (d) Secondary clay

Table 7.
Expansion percretage of Mold

	Expansion (%)		Weight (gm) (loss%)	
	Diameter	length	Dried at 35^0C	Fired at 1000^0C
Primary mold clay	1.44%	1.36%	39.9	38.4 (-3.75%)
Secondary mold clay	0.63%	0.46%	39.4	37 (-6.09%)



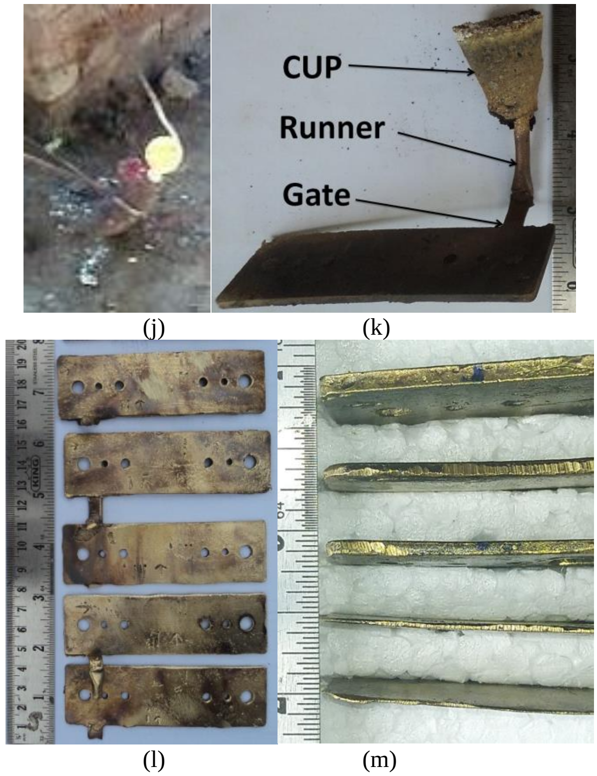


Fig. 6. Casting procedure of the sheets: (a) liquid wax pouing into the die, (b) rolling, (c) shaving, (d) cutting of the holes, (e) side view of all dies, (f) side view of all wax sheets, (g) few wax patterns, (h) primary clay coating, (i) clay mold having secondary and final clay coating, (j) liquid metal pouring in the red (k) cast plate with gating system, hot mold, (l) finished sheets, (m) side view of the sheet

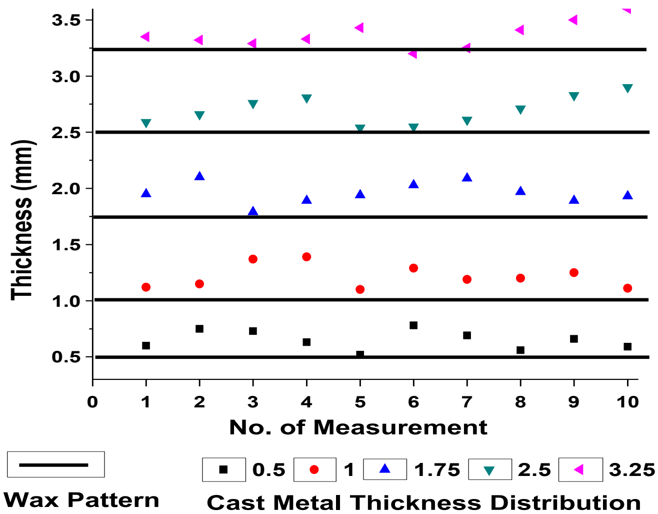


Fig. 7. Dimensional distribution of cast metal thickness along with wax pattern thickness

Table 8.
Cast metal thickness Expanion (-ve shrinkage)

Wax Pattern Thickness (mm)	$0.5^{+0.05}_{-0.05}$	$1.0^{+0.1}_{-0.1}$	$1.75^{+0.1}_{-0.1}$	$2.5^{+0.1}_{-0.1}$	$3.25^{+0.1}_{-0.1}$
Avg. Metal Thickness (mm)	0.65	1.21	1.95	2.69	3.36
Avg. Expansion (%)	-30.2	-21.7	-11.88	-7.84	-3.63

Table 9.
Shrinkage / expansion of clay Mold based on heating and cooling sequences at different stages

	Mold side	**Pattern or Cavity**	**Mold side**
Stage-I Molding	**Mold (wet clay)**	**Wax Pattern**	**Mold (wet clay)**
Stage-II Drying of mold	**Drying (Shrink)** →	**Wax Pattern**	← **Drying (Shrink)**
Stage-III Heating in furnace	← **Expand**	**Wax vapoured Cavity formed**	**Expand** →
Stage-IV Molted metal pouring	← **Expand**	↓ **Metal Filling** ↓	**Expand** →
Stage-V Cooling	**No Change**	**L –L & L –S Shrinkage Liquid Metal Supply from Cup/ Riser**	**No Change**
Stage-VI Cooling and Solidification	**Initial Mold Wall**	**S-S Shrinkage Final Casting**	**Final Mold Wall**

Initial mold wall: -------; intermediate mold wall: ———; final mold wall: ———; L-L: liquid-liquid; L-S: liquid-solid; S-S: solid-solid.

5. Conclusions

The following conclusions can be drawn on the basis of the investigation.

i. Major part of the mold was secondary mold or backing mold which contains 60%-70% silica sand. At 870^{0}C silica sand expand approximately 12.44% by volume. This is the main cause behind the expansion of the mold.
ii. Solidification is very slow for this process. As the liquid metal was poured into a hot mold which was even hotter than liquid metal. So, the sprue and cup fulfilled the function of the riser.
iii. The shrinkage or expansion of clay mold based on heating and cooling sequences at different stages has been shown in table-10.
iv. The Engraving Brass (2% lead) has a very small shrinkage allowance (thermal expansion co-efficient 20.5 µm/m °C) [15]. The metal shrinkage may not overcome the increased amount of mold cavity volume for thin-walled casting.
v. Expansion of the mold cavity is becoming higher than solid-solid shrinkage of the thin-walled Engraving Brass (2% lead) casting.
vi. With the increase of metal thickness the dilation percentage getting decreases, as the solid-solid contraction is more for the thicker section but the expansion of mold is almost constant.

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