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New Development in Investment Casting Process -A Review

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ABSTRACT- Investment Casting is a oldest casting process, used for precision casting and near net shape. It invented in around 3500 BC .This casting process is practiced in india and all over the world for high precision casting. Its product demand is growing in india as well as around the world.The use of simulation and Rapid prototyping (RP) techniques further increases its quality and same time reduce the lead-time and cost in investment casting process.The paper describes the role of rapid prototyping in product development through Investment Casting process and the scope of investment casting in India and around the world.

1. INTRODUCTION

Investment Casting is the one of the oldest casting process and most advanced in the metallurgical arts. This process is also knows as precision casting because it eliminates parting line and machining cost. This is a process of shaping metals where ceramic mold materials are invested layer by layer around an expendable wax or other materials that is the replica of desired article; the replica is then replaced with molten metal that solidifies in the shape of the desired article. This process is as ancient as the Harappan Civilization in 3500BC where, the bronze casting of a dancing girl (fig.1) was found (1). Archaeologist have established that the bronze images of Lord Buddha at Amaravati and Lord Rama and Kartikeya in the Guntur district of India were investment cast during the 3rd and 4th centuries AD (2). All these and many more bronze icons recovered from several places in India such as Saranath, Sirpur, Akota, Vasantagadh, Chhatarhi, Barmer and Chambi used natural bee-wax for patterns, clay for the moulds and manually operated bellows for stoking furnaces. During World War II, this technique was adapted to produce castings which could not be fabricated by other casting methods. Traditionally used for the creation of jewellery and art objects, the need for mass production of near net shape components during the 20th century led to the industrial development of the precision investment casting process. Today this ancient process is more relevant than ever, influencing and enhancing our daily lives, through leisure pursuits, air travel, medical implants, power generation, spare parts for textile, transport and other industries . In india There are about 200 industrial investment casting foundries in comparison with over 4500 sand and die-casting foundries.

Figure-1

Figure-2

Figure-1 The dancing girl from Mohenjo-daro. Harappan, 2500 BC. Lost wax copper alloy casting. (Photogravure1938, National Museum Delhi)

Figure-2. The Buddha from Sultanganj, Bihar. Gupta-Pala, 5th-7th century AD. Lost wax copper hollow casting.(Birmingham Museum and Art Gallery.)

Casting production has grown in most of the investment casting foundries in compare to previous years. Investment casting business in India is increased by approximately 10- 12% in the year 2011[3]. Many of these foundries are equipped with modern wax injection machine and robotic shelling system.They are majorly manufacture industrial valves, pumps and machinery which cover approximately 44% of Indian investment casting market.In defense field turbine blades and vanes for MIG aircrafts began in India during 1960s at HAL, Koraput by investment casting process.Currently,Racing car engines and aerospace industry find huge area of application of the investment cast graphite fibre-reinforced metal matrix composites[4]. Titanium and zirconium alloys have unique properties and are effective in aerospace and high performance structures. Even nickel-based super alloys[5] are being cast by vacuum investment casting process.

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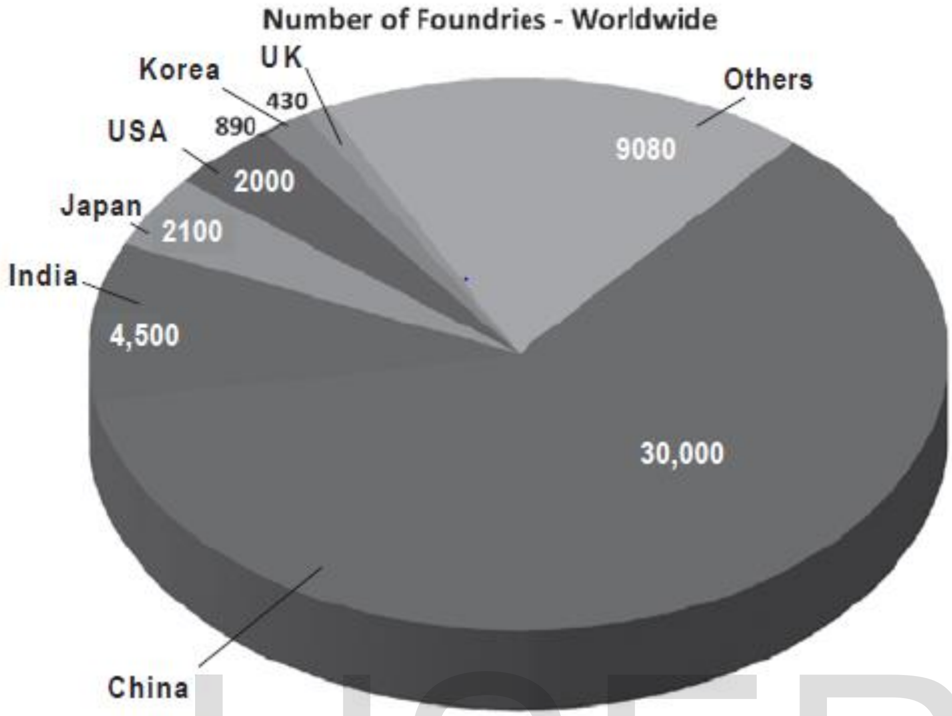

Figure-3.Distribution of Foundries across the world.

The distribution of nearly 1600 investment casting foundries worldwide is shown in Fig. 2[6]. Approximately, 75% of these investment casting foundries are in Asian countries. However, North America is the largest single producer of investment casting with almost 37% of the world sales while Asian countries' sales is approximately 33% (2011 data)[6].

In investment casting, the ceramic molds are made by two different methods: the solid mold process and the ceramic shell process. The solid mold process is mainly used for dental and jewelry castings, currently has only a small role in engineering applications.The ceramic shell process has become the predominant technique for a majority of engineering applications, displacing the solid mold process. The ceramic shell process is a precision casting process, uniquely developed and adapted to produce complex-shaped castings, to near-net-shape, and in numerous alloys. Continued advancements in materials and techniques used in the process, are driven and supported by R&D on many fronts, both in the industry as well as in many schools for foundry metallurgy.

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The Basic Steps in the Investment Casting Process

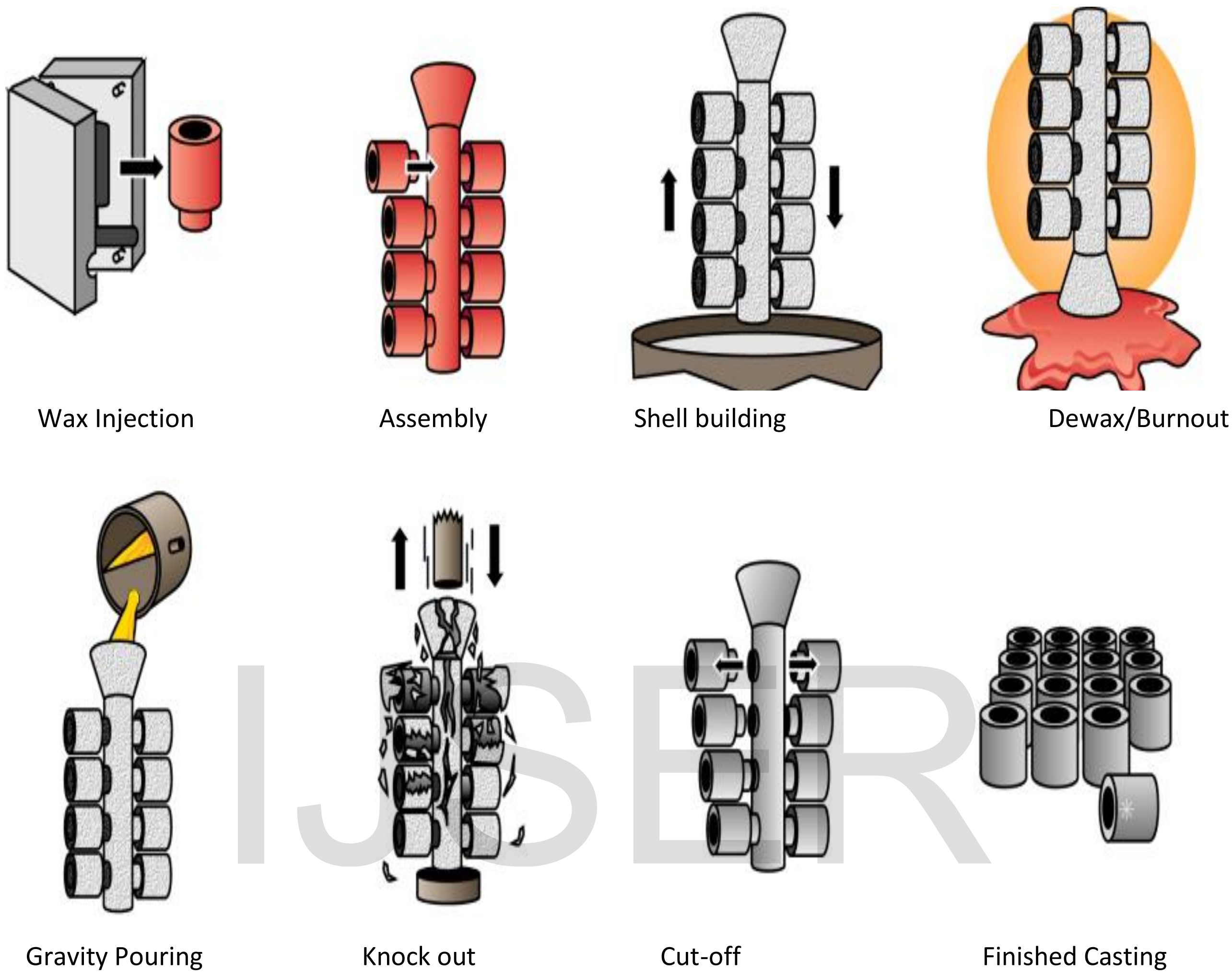

Figure-4.

2.Pattern Making

Wax patterns are traditionally[7] moulded in a permanent cavity known as “die”, which generally includes the ingates. The wax is injected in the die under 5-35 kg/cm2 pressure, often (but not necessarily) through the ingate. A separating agent is used to prevent sticking. A temperature of approximately 50^0C is critical. If it is too cold, details will suffer; if too hot, shrinkage of the wax will be excessive and time will be lost in chilling. After a desired cooling period to form up the wax pattern, the die is opened and the wax pattern removed.Instead of using metals as die materials, non-metals like polyurethane (to yield hard moulds) or RTV (to give soft moulds) can be used to make dies. A research study[8] has shown that polyurethane dies give patterns of better surface finish and accuracy. The study has also shown that using lower pressure with higher temperature for the polyurethane die will produce an accurate pattern provided that care is taken while choosing the holding time. A short holding time will produce more accurate pattern but too short a holding time will cause distortion while removing it fromthe mould, as it might be too soft. Patterns suitable for investment casting can be built using RP systems such as Fused Deposition Modeling [9], Stereolithography and Thermojet [10], ZPrinter [11] and Layered Object Manufacturing [12]. In liquid-based systems, the portions of the part lying above any undercuts are supported on independent structures created along with the part (using a different material as in FDM, or the same material as in Stereolithography).

3. Pattern Materials

3.1. Pattern Waxes

Waxes are mostly the preferred material for patterns, and are normally used, modified and blended with additive materials such as plastics, resins, fillers, antioxidants, and dyes, in order to improve their properties, [13]. Paraffins and micro crystalline waxes are the most widely used waxes, and are often used in combination, because their properties tend to be complementary. Paraffin waxes are available in many controlled grades, with melting points ranging from 52 to 68 °C (126 to 156 °F). They are readily available in different grades, have low cost, high lubricity and low melt viscosity. Their usage is, however, limited because of high shrinkage and brittleness.

3.2. Plastics

Plastic is the most widely used pattern material, next to wax. Polystyrene is usually used, because it is economical, very stable, can be molded at high production rates on automatic equipment, and has high resistance to handling damage, even in extremely thin sections. Use of polystyrene is however limited, because of its tendency to cause shell mold cracking during pattern removal, and it requires more expensive tooling and injection equipment than for wax. However, the most important application for polystyrene is for delicate airfoils, used in composite wax-plastic integral rotor and nozzle patterns, assembled using wax for the rest of the assembly.

3.3 Mercury pattern compounds (Mercasting, 2006)

In this case frozen mercury is used as a pattern material instead of wax. Liquid mercury is poured into a mould where it freezes at low temperatures. Then it is removed and coated with cold refractory slurry to the required thickness. The refractory shell is dried at low temperature the sh parts be made using mercury. Very close tolerance obtained but it is a very expensive method.

3.4 Ice pattern compounds (Zhang, 1999)

It uses pure water to make the ice pattern . At low temperature, water is sprayed through a nozzle to a selected place under the computer's precise control, and is freezed rapidly. The solid part is built from the bottom up to the top layer-by-layer. The advantages of the ice are cheap, readily availability, contractions during melting, high quality, good surface finish and the environmently friendly nature of water. The ceramic moulds were done at sub-zero temperature in favor of the ice pattern used.

3.5. Other Pattern Materials

Foamed Polystyrene has long been used for gating system components. It is also used as patterns with thin ceramic shell molds in a separate casting process known as Replicast Process. Urea-based patterns, developed in Europe, have properties similar to plastics; they are very hard, strong and require high-pressure injection machines.

3.6. RP pattern

Use of Rapid prototyping (RP) techniques reduce the lead-time and cost in investment casting process. It also gives the freedom to issue new products rapidly without significant increase total development time and cost.The ideal RP pattern for investment casting is wax, such as Thermojet MJM wax and FDM ICW06 wax. However, based on Whovers' 2008-RP-Report in Fig. 1, more than 70% of RP units produce parts that are made of thermo plastic or thermo-set [14], simply because at present the RP units purchased by companies are used for multi-functions not only for demonstration and sampling, but also for fit and run pieces.There are several RP techniques available for fabrication of investment casting patterns such as: ABS (Acrylonitrile Butadiene Styrene) for FDM (Fuse Deposition Manufacturing) process [15], Quick CastTM photopolymer used in SLA (Stereo-Lithography) [16] and PrimeCast 100 polymer for SLS [17].

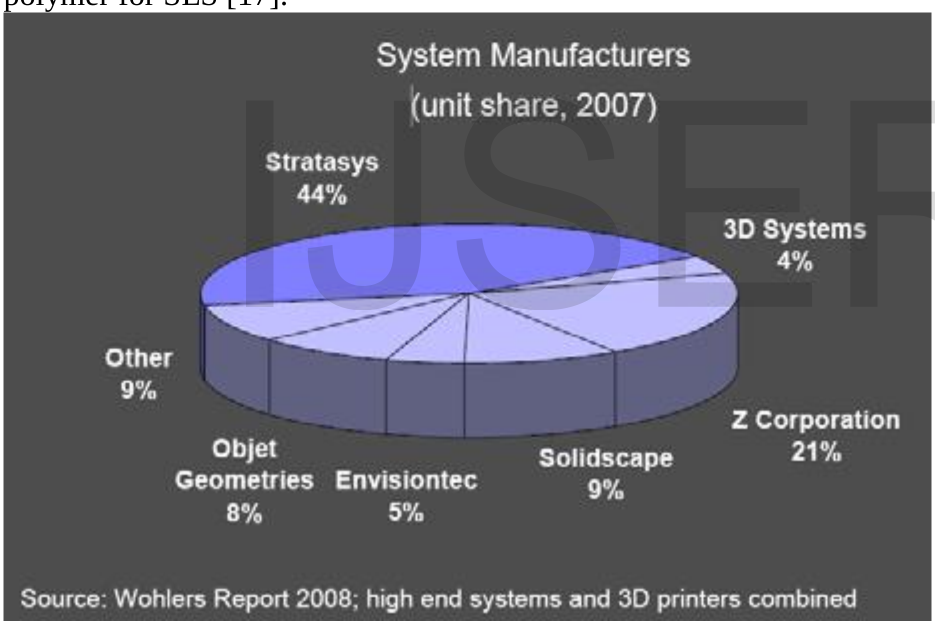

Figure-5

Suitable material for investment casting

A wide variety of materials such as both ferrous and non-ferrous can be used in investment casting. Any metal that can be melted in standard induction furnace or vacuum furnace can be considered for this case. Difficult to machine materials are also good candidate for investment casting. Comprehensive list of materials that can be used in investment casting are given in Table

Table 1: Suitable material for investment casting[18].

Material	Fluidity	Shrinkage	Resistance to hot tearing.	Castability rating
Carbon steels				
1040 (G10400)	B	B	B	B+
1050 (G10500)	B	B	B	B+
Alloy Steels				
2345 (G23450)	B	B	B	A-
4130 (G41300)	B	B	B	A-
Nickel Alloys				
Monel (QQ-N-288-A) (N04020)	A	B	B	B+
Inconel 600 (AMS 5665) (N06600)	A	B	B	B+
Cobalt Alloys				
Cobalt 21 (R30021)	A	A	B	A
Cobalt 31(R30031)	A	A	B	A
Aluminum alloys				
A 356 (A13560)	A	A	A	A+
C 355 (A33550)	A	A	A	A+
Tool steels				
A-2 (T30102)	B	B	B	B+
H-13 (T20813)	B	B	B	B+
Copper alloys				
Gunmetal (C90500)	A	C	A	B+
Beryllium copper 10C (C82000)	A	C	A	B+

A -Excellent; B - good; C- poor

4. Modeling and simulation

The use of simulation leads to increase in efficiency and decrease in the trial and error experiments in the casting process. Casting simulations involves design, visualization and optimization of the casting process before making expensive molds or patterns. During casting, thermal stresses occur in the cast parts which lead to different consequences such as distortion, crack, hot tear and residual stresses. Each one of them has detrimental effect on the quality of cast products. The simulation of thermal stress during solidification is an important way to predict the above mentioned defects in a casting.

Many simulational studies have been made in the field of investment castings. Guan et al. (1994) developed a thermo-mechanical model to calculate the residual stresses upon cooling, the resulting distortions and the cracking behavior of -TiAl investment castings. It was found from their study that the calculated and the experimental results of the castings showed good agreement with each other. The work carried out by the authors is really noticeable as they could predict the residual stress occurring in the casting proximately so that necessary actions could be taken to reduce or prevent the same. However, their model could not predict the temperature range accurately at which residual stress might occur. A similar work was done by Norouzi et al. (2009), who simulated the residual stresses and hot tearing in investment castings using MAGMASOFT simulation software. It was found that the temperature range for simulating residual stress was between room temperature and coherency temperature and the same for hot tearing was between coherency temperature and solidus temperature. The results also revealed that the thermal stress concentration zone increased the hot tearing probability and consequently reduced the amount of remaining residual stress in casting parts. The work done by the researchers is appreciable. Today, several major foundries around the world have bought and are using these kinds of simulation softwares. There is, also, a significant number of engineering companies performing foundry process simulation as a consultancy service for foundries. However, the problem arises with few small scale foundries which can neither buy these softwares nor hire the services of consultancy companies.Chattopadhyay (2010) built a functional relationship between the solidification time obtained from lumped analysis and full phase complete solution of energy equation, considering heat losses from the mold wall by both convection and radiation. Afazov et al. (2011) also developed a simulation package to predict the residual stresses in the bottom core vane (BCV) component of an aero-engine subjected to equiaxed cooling, using two finite element (FE) codes (ABAQUS and ProCAST). The temperature and the residual stresses have been compared for both FE codes. The results showed that both codes were suitable for carrying out casting simulations.Several casting simulation programs are available today and quite well established: Magma (www.magmasoft.com),Pamcast/Procast(www.esigroup.com),Novasolid/Novaflw (www.novacast.se), Solidcast (www.finitesolutions.com) and a few others. They are however, rarely used by the large number of small and medium size foundries, owing to the high cost of the software and support involved, and difficulty in attracting and retaining the technical manpower required to run the programs.

5. Rapid Prototype Technology and Investment Casting

In traditional Investment Casting the cost of tooling is higher for producing the wax pattern. As such, Investment Casting is not suitable for low volume production like rapid prototyping (RP) or specialized components productions. In rapid prototyping process 3-Dimension CAD model converting into a solid physical model directly. Taking advantages of computer hardware and software technologies, the CAD data of a three-dimensional object was sliced into multiple two-dimensional layers . RP fabricators generate a three-dimensional physical model by stacking thin layer cross-sections of the sliced part geometry from the CAD data.The first RP technique, namely sterolithography (SLA) was invented in 1986.After that,many other RP processes have been developed. First time in SriLanka, modeling of complex engine parts using by rapid prototype technique and subsequent mould making for investment casting using ceramic materials were performed.In the last few years there have been rapid developments in the accuracy, surface finish and build speed of RP parts. At present, there are almost 60 RP technology in use based on different materials and techniques for building and binding the layers .The RP technology that are used in investment casting process are Laser Stereolithography (SLA), Selective Laser Sintering (SLS), Laminated Object Manufacturing (LOM) , 3-D Printing (3DP) (or Direct Shell Production Casting, DSPC), Ballistic Particle Manufacturing (BPM), Sander Prototype (SPI), Laser-Engineered-Net-Shaping (LENS), and Fused Deposition Manufacturing (FDM).

The key advantage of rapid prototype technology is that it eliminates the need for tooling, reducing the lead time and make pattern quickly for a cast part.The output of rapid prototyping can be used directly as an expandable pattern or to produce investment wax patterns from rapid prototyping molds.Rapid prototyping is capable of generating thermally expandable patterns or toolings for fabricating permanent dies or molds for injections of investment wax patterns for shell investment casting.It provides a sharp tool for global competition by saving time and cost.There are several alternatives for involving rapid prototyping process in investment casting.

(a) Some rapid prototyping process is used for mold tooling for injection of investment wax patterns.

(b) Some rapid prototyping process can fabricate expandable patterns for casting.

(c) Some rapid prototyping processes can make ceramic cells directly for investment casting.

Table 2.shows the compatibility of various RP technologies with investment casting. It includes the material availability, pattern accuracy, toxicity and the transferability of pattern removal.

Table-2. The compatibility of RP processes with investment casting.

RP Process	Material	Accuracy	Trancferability	Material toxicity
SLA	Epoxy	Excellent	Thermal Expansion	Yes
SLS	Casting wax, Ploycarbonate	Poor	Material shrinkage	Yes
FDM	Casting wax	Good	Similar to Lost wax	No
SPI Model Maker	Low melting Thermoplastic	Excellent	Negligible thermal expansion	No
DSPC	Casting ceramic	Poor	Material shrinkage	Yes
LOM	Sheet paper	Fair	Residual ash	Yes

Conclusion. In this article, some of the latest developments in the investment casting have been discussed and the process characteristics highlighted.The ancient investment casting process is a slow and troublesome and it makes the product costlier. India has proven capability in the ancient art of metal casting as well as the latest information technologies, but needs to combine these capabilities to surge ahead in the global race of competitive manufacturing. . One such proposed route is through computer-aided design and rapid prototyping technologies for pattern development, followed by clay-moulded (ancient) or ceramic shell (current) methods for investment casting. However, with reducing costs of the systems involved and improving efficiency of the processes, we strongly feel that the approach will gradually expand its reach. It is important for the foundries to experiment with such new routes, identify the best combination of application, geometry, material and process, and specialise in that combination to establish a niche in the global market.

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