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PRODUCTIVITY ENHANCEMENT IN INVESTMENT CASTING FOUNDRY USING AUTOMATION TECHNIQUE IN SHELLING OPERATION

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Abstract

The investment casting industry falls under the highly technological but extremely labor-intensive industry. The increasing need of the complexity, close dimensional accuracy and high reliability of the castings at the most competitive cost has become basic necessity for sustaining growth in the global market place. The purpose of this paper is to study the present manual processes in the Indian investment casting industry and to identify the opportunities to automate them and evaluate its impact on the product quality, productivity and yield which are essential performance parameters for investment casting industry. The approach adopted is to identify and study all the manual processes in the foundry, rejection analysis of a foundry using Pareto analysis followed by cause-effect analysis for defects arising from the manual activities using Ishikawa diagram. Reasoning of shell shop selection for automation and limitation of existing manual layout has been discussed. Process automation using robotics in shell shop uses robot for repetitive dipping, coating and drying cycles on each mould resulted in reducing rejection from 11.2 % to 3.5 %, cycle time reduction from 4-5 days to 2-3 days, improvement in yield from 29 % to 38 % and productivity from 27 % to 32%. Absence of programmer's skills to coat complex geometries to achieve better results is the constraint of the shell automation technique. Higher capital cost restricts the use of robot in wax assembly, foundry shop and post casting operations.

Keywords: ***investment casting, automation & robotics, quality & productivity.***

1. INTRODUCTION

Conventionally, the foundry is extreme labor-intensive industry. The increasing cost of labor force, need of higher manual skills and higher pollution to environment has been the root causes to close down of the foundries in Europe and sourcing the castings from India and other developing industries. The investment foundry has also seen similar trend since nineties of the last century. The investment casting industry falls under the higher technological branch of the foundry industry. The Indian companies which were associated with European market by means of technology transfer or participation through business fairs, got good realization of the efforts as compared with the Indian customer as it was win-win for both the parties. The increasing complexity due to extensive use of 3D designing and product modelling tools demands higher repeatability and higher dimensional accuracy. The growth and acceptance of the Chinese industries to the European customers has intensified the competition and pushed the margins to the bottom levels and thus the lower cost ofproduction and high reliability standards became essential elements for survival. The analysis of 'costing of casting' reveals that the average monthly rejection of the casting is in the range of average 12% to 20% to Indian foundries as compared to 4% to 6% in European foundries. There are two approaches to increase 'good castings produced per mould'; One by reducing the rejection of the casting and secondly increasing the number of castings assembled on the mould. Rejection of casting can be reduced by avoiding defects that come through manual activity and using automation. The increase in number of castings per mould is restricted by the total weight and size of the mould as these moulds are handled manually which can increase the rejections due to handling difficulties by the operator. The purpose of this paper is to study the losses due to poor quality and higher rejection in the processes due to present manual process controls in the Indian IC industry and to measure the benefits of process automation as well its impact on the productivity and yield which are other essential performance parameters for IC industry. literature related to various areas of foundry which are using automation and robotic technique has been discussed in following section.

2. LITERATURE REVIEW

The final casting product has to pass through the various stages of investment casting and precise control on parameters using automation at these stages can enhance the quality in product by reducing the defects. Wax stage, mould stage, casting stage, and post casting stages are the major stages of investment casting. Conventionally wax patterns are produced by automatic machines but not the assembly. The benefits of automation in the assembly process of wax pattern has been reported by Mahrabi (2016). Precision welding of wax patterns on riser plate reduces the inclusion, saves energy and minimize wastage. Accurate alignment of wax patterns also enables to facilitates the easiness in automation of post casting processes. Ludwig et al. (2006) invented automated process of wax assembly using robot and claimed that the produced components are highly accurate, repeatable, dependable still economical as reduces rate of casting rejections. Added benefit of uniform shell coverage which results due to extremely consistent and accurate wax assemblies improves uniform heat transfer and metallurgical properties. Robots are widely used in industry for positioning, orienting and handling of parts in automated assembly production. Wadhwa (2014) presented the extensive literature review on gripper and proposed design of different grippers to handle the variety of cast part in flexible automated assembly lines. Rooks (1996) reported in his detail case study of foundry automation where the use of gantry and articulated robot of ABB company has been used for handling, loading unloading, palletizing of cores, moulds, pouring and casting.

Koffron (2001)invented a computer-controlled metal pouring system by adjusting the furnace tilt angle and using sensors. This minimize vortex formation and minimize slag entrainment due to minimization of operator error. Kulkarni et al. (2018) designed the robotic system for automatic pouring using PLC to reduce the casting defect as well as to provide safety and health to workers. Automation is also applied in removal of shell in investment casting by using high pressure pump and rotating nozzle in robotic water jet system effectively which results increase in output, decrease in noise and fatigue of operator reported by Cashman (2015). Use of robots in post processing applications, such as grinding, polishing and deburring's of the cast part has been studied by Brussel and Persoons (1996). Fettling is the most labour-intensive process as compared to all stages and finds major application for automation. Geometrical and material variation of casting causes problems in fettling automation using robotics which was analyzed by Warnecke (1983). A novel approach to the design of an automated system for non-destructive radiography test for castings has been described by Kehoe and Parker (1992). The system uses intelligent knowledge-based system and traditional image processing techniques together interprets and investigate radiographic images. Use of computer simulation for checking the filling and solidification defect before actual casting trial is the major development in recent years. This saves cost and time due to reduced number of casting trials. Chalekar et al. (2015) described the simulation approach to reduce these defects. Majority of the research has been carried out in use of automation/robotics technique in wax, casting and post casting stages. This work presents emerging trend of automation and robotics in shelling operation which is the key and unique process differentiate IC process from other casting process. The systematic approach to justify the deployment of robotics in shelling shop using CTQ (critical to quality) approach has been presented. Advantages of robotics layout over manual layout for shelling process has been studied and presented in detail.

3. METHODOLOGY

The methodology for the work is described below.

1. Study of the investment casting process to understand manual work content with process flow diagram.
2. Identifying the CTQ's of the process, their current level of process control, manual / machine control, recording of the assurance of the process CTQ's and identify the weak process link in the quality chain.
3. Pareto analysis of the foundry data for majority of casting defect.
4. Study of the top four defects and establish the relationship of defect with the identified weak process link using cause effect analysis.
5. To study the man- material movement and elements of operator's consistent skills requirement in identified weak process link.
6. To evaluate the process automation alternative along with the layout and benefits on the control on process CTQ's.
7. Comparison of the impact of automation on the monthly rejection analysis of the foundry and other benefits in terms of yield and the labour productivity.

3.1 Study of Investment Casting Process along with Process Flow diagram

The investment casting manufacturing can be divided in four manufacturing sections and their process flow is shown in the Table 1.

3.1.1 Wax Shop

In investment casting initial stage is the wax stage where wax patterns and riser plates are produced using water cooled, CNC machined, aluminum dies on automatic wax injection moulding machine. Wax pattern ejection, handling, pattern frazing, inspection and correction, wax tree assembly is a precise and light manual work.

Table 1: Process flow diagram

Section	Process No	Process Name
Wax Shop	10	Pattern Making
	20	Frazing, inspection & correction
	30	Assembly of tree
Shell Shop	40	Shell Coating
	50	De Waxing in Auto Clave
Foundry	60	Pre heating & Sintering
	70	Metal Pouring
Fettling & Finishing	80	Knock out shell
	90	Fettling casting
	100	Finishing
	110	Shot Blasting
	120	Inspection
	130	Final Finishing
	140	Oiling and storage

3.1.2 Shell shop

The wax tree assembly is coated to form ceramic mould by dipping in to the ceramic slurry drum and holding below sand shower for stuccoing. The assembly is slowly rotated to ensure covering of all the corners, cavities of the each intricated wax patterns with thin and uniform layer of the ceramic slurry and stucco. The coated mould is properly dried after each coat before applying next slurry coat. The complete shell atmosphere is temperature and humidity-controlled shop to be maintained for uniform drying time of 8 to 12 hours. Air circulation is also very high with the help of industrial fans to ensure all the moulds get dried from all the intricate shapes and corner of the patterns. This complete process is called one coat of the ceramics and with every coat of ceramics the thickness of the shell increase. The process is repeated minimum 7 to 14 times for every mould based on their process sheets to achieve the desired shell thickness of minimum 6 to 20 mm. After final drying of the shell, the shell is loaded in the autoclave and the wax is removed by pressurizing the chamber with sudden entry of hot steam under pressure of 8-15 Kg/cm^2 within 8 seconds to avoid the cracking and bursting of the shell due to expansion of the wax inside the shell.

3.1.3 Foundry

The de-waxed shells are loaded normally in the LDO fired preheating furnaces, these furnaces are chamber type furnaces where 1050-1000°C temperature is maintained continuously. Normally the batch takes one hour to reach the of the furnace and one-hour soaking is carried out to ensure uniform heating of the ceramic shell. Simultaneously, the desired composition of the metal is melted in the induction furnace, after checking the temperature and composition, molten metal is poured immediately in preheated mold and allowed to solidify. The working area is dull, dirty and dangerous not suitable for human.

3.1.4 Fettling and finishing

After solidification and cooling of mould the shell from the mould is removed in the knockout machine with the help of pneumatic hammers machine, and then each casting is separated by rod cutting, gas cutting, abrasive parting wheel or band saw. The feed excess metal is removed using belt grinder and the surface of the part is blasted by sand or small metallic balls in shot blasting machines. Any surface irregularities if exists, are removed using pencil grinders. This process repeated till the casting surface quality achieves the acceptable range. The complete process is totally manual, very laborious, hard working in dusty environment. Normally sub-contracting is preferred to minimize the casting cost.

3.2 Process CTQ's and it's control mechanism

The four key departments of investment casting are having 14 basic processes are listed in the process flow diagram as shown in Table 2. The process "Critical to Quality" CTQ's for each of the process are discussed and listed in Table 3. The control mechanism whether it is machine controlled / automatic or manually controlled is also identified and recorded. It is also necessary to understand whether the quality of the process can be inspected and rectified or not after completing the process. In any activity if no inspection or rectification is possible, then the control of the process is become very critical for the quality of the product.

Table 2: Process wise critical to quality (CTQ) code

Section	Process NO.	Process name	CTQ code	Process CTQ	Machine control	Manual skill
Wax shop	10	Pattern making	W1 W2 W3 W4	Wax temp Injection Pressure Holder timer Chill water temp	Yes Yes Yes Yes	
	20	Frazing, Inspection and correction	W5	Quality checks		Yes
	30	Assembly of tree	W6 W7 W8	Joint Quality Feed design Angle and position of patterns	 Yes 	Yes Yes
Shell shop	40	Shell coating	S1 S2 S3 S4 S5 S6 S7	Slurry viscosity Slurry plate weight Process sequence Uniform coat Drying time Air circulation Air quality –	 Yes	Yes Yes Yes Yes Yes Yes

			S8	temp., humidity Inspection during coats		Yes
	50	Dewaxing in autoclave	S9 S10 S11	Steam pressure Steam temperature Holding time	Yes Yes Yes	
Foundry	60	Preheating and sintering	C1 C2 C3	Furnace temperature Heating time Loading quantity	Yes Yes Yes	
	70	Metal pouring	C4 C5 C6 C7 C8 C9 C10	Metal temperature Metal composition Impurity in metal Pouring time ladle time Metal flow rate Shell hold time	Yes Yes	Yes Yes Yes Yes Yes
Fettling and finishing	80	Knock out shell	F1 F2	Safe handling Vibration time		Yes Yes
	90	Fettling and casting	F3 F4 F5	Cutting point Cutting force Cutter size	Yes	Yes Yes
	100	Finishing	F6 F7 F8	Grinding belt grit size Grinding force Feed pad projection	Yes	Yes Yes
	110	Shot blasting	F9 F10 F11	Shot size Shot material type Blasting time	Yes Yes Yes	
	120	Inspection	F12 F13	Visual check list Sorting for Ok / repair / reject		Yes Yes
	130	Final finishing	F14 F15 F16	Shot size Shot material type Blasting time	Yes Yes	Yes
	140	Oiling and storage	F17 F18	Oil quality and type Dipping time	Yes	Yes

Table 3. Process classification and CTQ's and their control mechanism

Production Shops	Number of Processes	Inspection & Rectification possibility	Process CTQ	Machine Control	Manual Control
Wax Shop	3	3	8	5	3
Shell Shop	2	0	11	4	7
Foundry	2	1	10	5	5
Fettling & Finishing	7	7	18	8	10

It can be identified that the shell shop process "shell coating" and foundry process "metal pouring" are weakest processes from inspection and rectification point of view. Similarly, the study of Process CTQ control mechanism reveals that the manual control is very high in these processes. Similarly, the manual content and control is very high in fettling and finishing operation also, but inspection and rectification possibilities exists, hence having lower weightage for process automation. To minimize the process cost, these processes are also sub-contracted for reduction of the total cost.

3.3 Pareto analysis of the foundry data for majority of the casting defect.

The average production of 8000 to 10000 mould / month is the trend of production of IC foundry considered for study. Cause wise rejection of each mould are recorded after casting and first levels of fettling. As finishing continues in each stage such as sand blasting, shot blasting the rejections are tracked and recorded against the production. Finally, in crack or chemically off inspection rejection are recorded stage wise. For about 250 variety of casting, good castings and rejected casting has been recorded and percentage calculated in terms of casting which is around 17 %, the breakup of total defect is shown in pareto analysis. The total rejection of a typical IC industry for a specified month is classified on the defect codes and shown in the Fig. 1: -Inclusion, Not Filling, Extra Metal and Shrinkage are top four defect in IC process as having high rejection percentage.

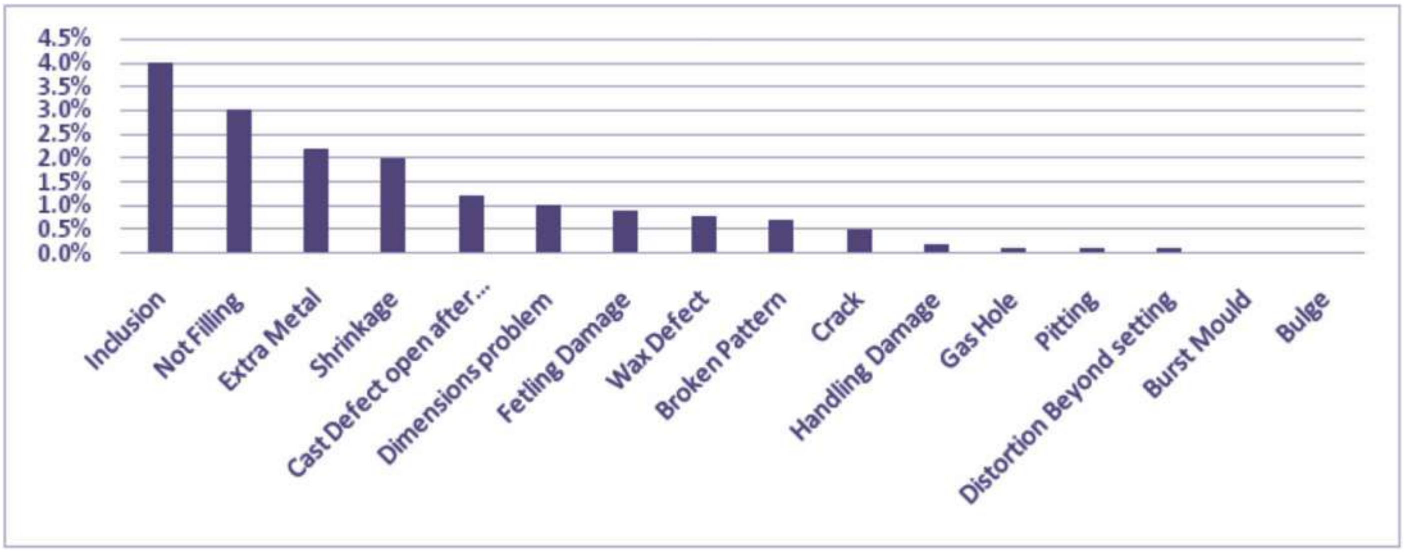


Fig 1. Typical Pareto Analysis of the Casting Defect in Investment Casting Industry

3.4 Ishikawa diagrams to identify the critical process:

Four major defects and their causes has been represented in Figure 2 in the form of fish bone diagram. The causes from each section are linked with the process CTQ's to relate the cause-effect relationship which further investigated for the analysing the defect wise relationship with the operation department. These defects have been compared shop wise as shown in Table 4 which reveals that shell shop is the major source of most of the casting defects followed by foundry section due to lack of process quality control. In this research shell shop is selected for automation study as the key section which causes most of the defects.

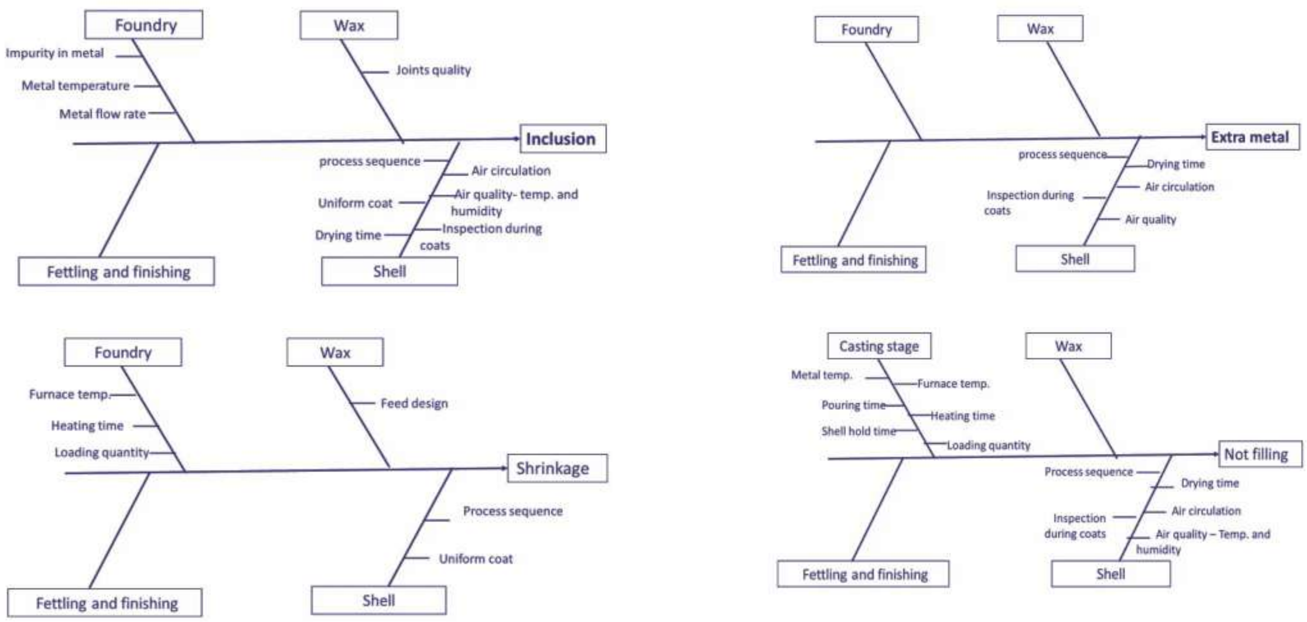


Fig.2. Ishikawa - Cause and effect diagram for four main selected defects:
(a)-Inclusion (b)-Extra metal (c)- Shrinkage (d) -Not filling.

Table 4. Shop wise defect relationship

Defect	Rejection %	Wax	Shell	Foundry	F & F
Inclusion	4.0%		■	■	
Not Filling	3.0%		■	■	
Extra Metal	2.2%		■		
Shrinkage	2.0%		■		
Defect open after machining	1.2%		■	■	
Dimensions problem	1.0%	■	■	■	■
Fettling Damage	0.9%				■
Wax Defect	0.8%	■			
Broken Pattern	0.7%		■		
Crack	0.5%		■		

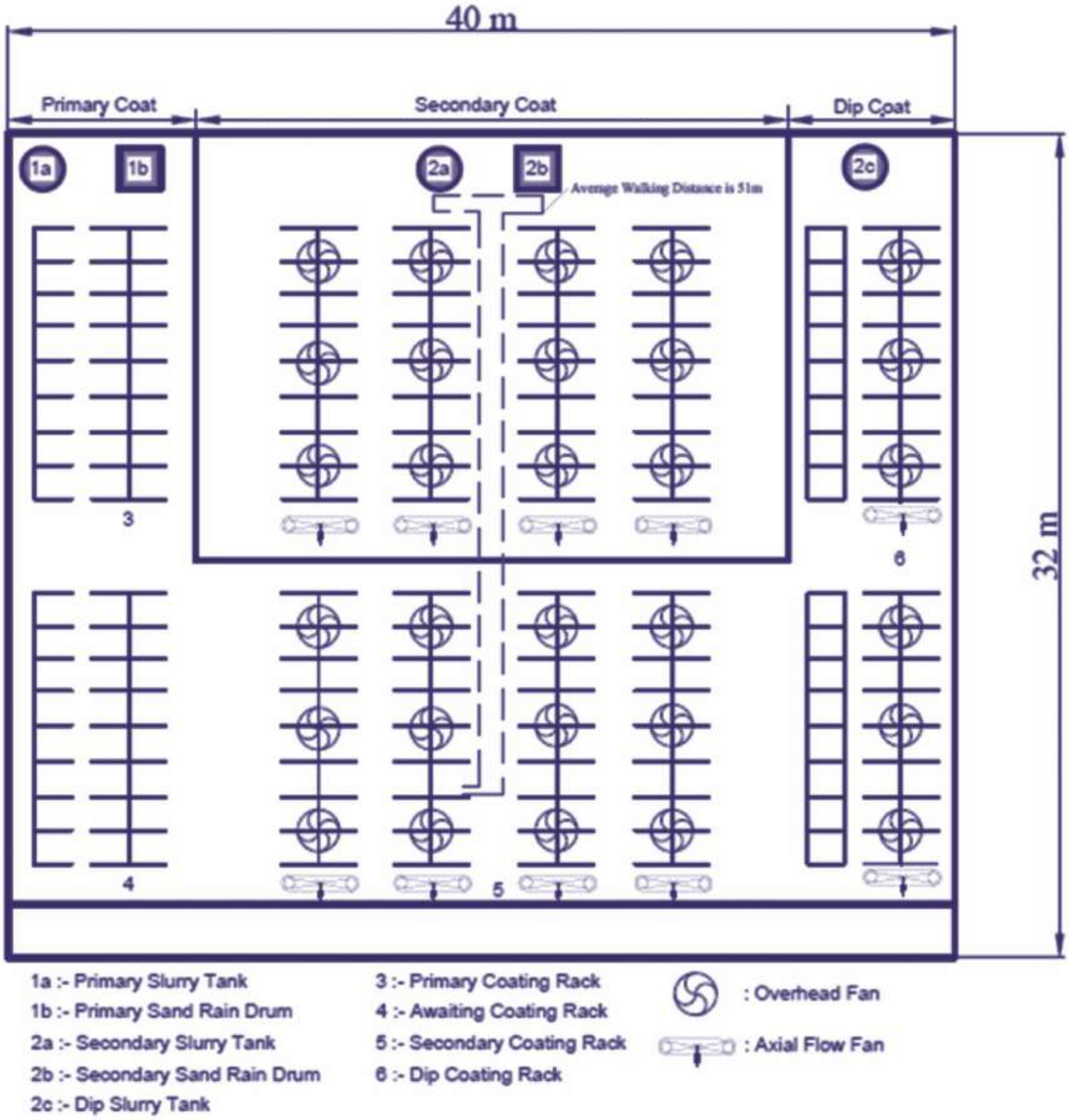


Fig. 3 Existing shell shop layout for manual handling

3.5 Existing shell layout (manual)

Present shell shop plant layout is as shown in the Figure 3. The shell shop is having temperature and humidity control mechanism with number of overhead and axial fans to generate and circulate air flow across the shell shop. The primary slurry tank 1(a) and sand rain drum (1b) are kept near the entry side of the shop. The new wax trees are fed from the entry gate of the shell shop. The shells are stored on open four-layer racks with three shells in a queue on each rack. The adjacent racks are used to keep the shells for drying after primary coats. Similarly, the secondary coating slurry tank 2(a) and sand drum 2(b) are kept at the center of the shop so that the distance travel for operator to coat each shell should be uniform. Each rack is having one loading sheet on which the present moulds, and their actual coating time for each coat are recorded so that the correct numberof coats should be controlled as well the in between drying time is also ensured which are critical CTQ's for the process. The coating sequence is very critical to quality to repeat for every coating to the mould. The slow and steady entry of the mould in the slurry tank, slow rotation of mould in the tank, slow withdrawal from the tank and holding the tree in inclined position with slow rotation toensure covering of the intricatepart of the geometry as well draining of the excess slurry and uniformity of the coating thickness takes place. Similar precautions are needed for the sand rain drum process.

3.6 The drawback of the existing (manual) shell layout -

a. The operator has to give around 200 coats in 8 hours on regular interval. The process has to continue round the clock for 24 hours. The consistency of first coat to the shift end coats differ due to fatigue of the operator.

b. Each mould has to be taken from rack, coat it and again reload on the same rack. The distance travelled out is approximately 50 meters per mould with carrying the weight of approximately 8 Kg. Thus, walking around 10 Km per day with 8 kg of load is very hectic.

c. The wax assembly/shell mould is very delicate, so any jerky motion or touching to any static structure with carrying causes damage partially or completely. Lot of care is to be taken while carrying or coating on the mould.

d. The working is expected to be continuous without break so uniform drying time is provided which is difficult to achieve due operators rest and work practices.

e. The process CTQ's of shell shop and it's dependent on the operator's skill, consistency is shown in Table 5. The highlighted CTQ's are operator dependent and are sensitive to quality as no inspection & rectification is possible after completing the process.

Table 5 : Shell Shop Coating process CTQ's and its control practices

CTQ Code	Process CTQ	Machine Control	Manual Skill	Inspection & Rectification
S1	Slurry Viscosity		Yes	Yes
S2	Slurry Plate Weight		Yes	Yes
S3	Process Sequence		Yes	No
S4	Uniform Coat		Yes	No
S5	Drying Time		Yes	No
S6	Air Circulation		Yes	No
S7	Air Quality - Temp & Humidity		Yes	Auto
S8	Inspection during coats		Yes	Yes

3.7 Study of shell shop automation: -

To overcome the limitation of manual layout, automation of shell plant is proposed. The 7-axis robotic arm with transverse movement and auto gripper mechanism which is coupled with the three-layer chain driven conveyor system is used for process automation and handling and is shown in Figure 4. The complete logic is computer programmed. The coating sequence is repeated round the clock in the same manner to ensure consistency of the coating process. The hanger can carry up to 6-8 moulds depending on the construction, in one operation, so that the productivity is around 6 time than one operator. The coupled conveyor acts as racks for proper air drying and material movement of the mould. The computer also controls the gap between two coats to ensure good drying of the moulds. Thus, all the shortcoming of the manual process is taken care and all the manual CTQ's are automatically controlled. The details steps of the shelling process are shown in Figure 5.

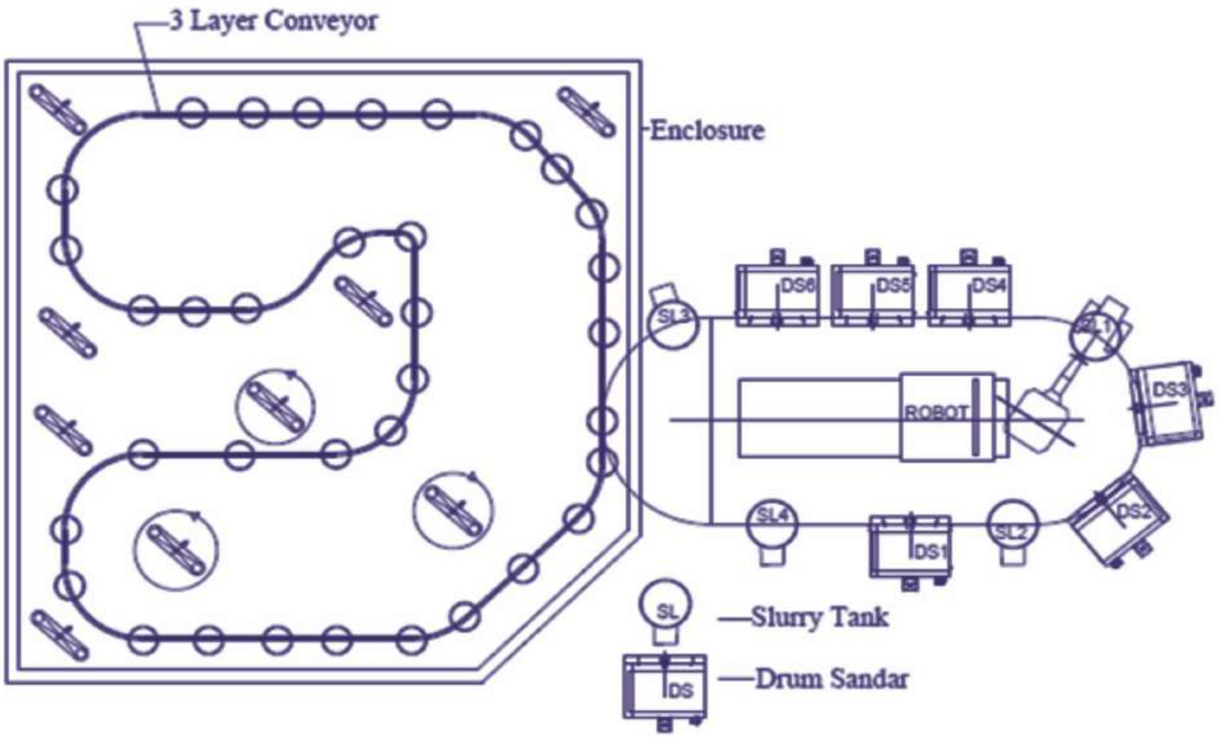
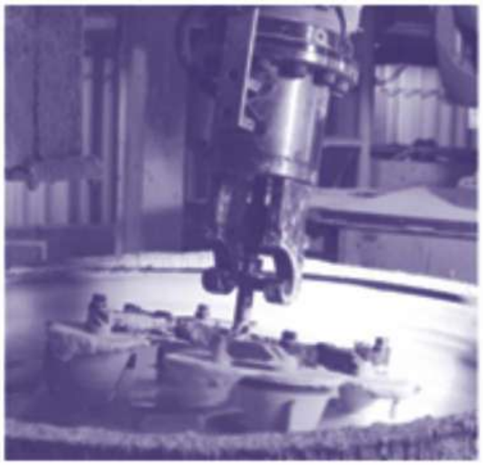


Fig. 4: Robotic shell shop layout

(a) Robotic layout supplied by AV robotics



(b) Dipping of wax tree in slurry tank [ABB robot]

(c) Rain drum used in robotics shelling [ABB robot]

Fig. 5 Robot used for shelling operations

4. RESULTS AND DISCUSSIONS

Comparative study of manual and robotic shell shop in relation to rejection due to defect is shown in Table 6. other benefits of automation also discussed here with.

(a) The rejection analysis: - The largest rejection in investment casting has been observed due to four major casting defects such as inclusion, not fill, extra metal and shrinkage. (a) Inclusion: The nonmetallic particles in solidified casting referred as inclusion. The loose sand trapped in corners of ceramic mould is one of the major sources of inclusion. Non-uniform coating, improper drying of shell is the main cause of ceramic inclusion. (b) Not fill: The last unreachable or complicated corner of mould is not get filled due to drop in molten metal temperature during filling. Undesirable thick coating at critical sections results in less heating of inside mould which solidifies molten metal before reaching to the last corner. (c) Extra metal: Poured hot molten metal in mould punctures the weak shell and gets solidified with sand particles. This cannot be removed from critical areas by sand blasting and shot peening. Improper drying of shell reduces strength of the shell (d) Shrinkage: uneven shelling and improper cooling of shell causes non-uniform heat transfer thus results in non-uniform shrinkage rate and produces shrinkage cavity defect. The shell making process is the major source for all these defects.

Process automation in shell shop uses robot for repetitive dipping, draining, stuccoing steps. Precise control on entering angle in slurry tank, draining angle, rotation speed results reach of uniform coat all over mould. Air circulation around the mould from all the angles due to better design and movement of the conveyor loops results proper drying of all shells. All these features reduce the inclusion, not fill, extra metal and shrinkage cavity defect. Table 6 shows percentage reduction in major defect due to use of automation in shell shop. The study of the monthly rejection analysis of the same foundry reveals that selected four defects of the investment foundry has been substantially reduced from 11.2% to 3.5%, saving of around 8.7% over the overall rejection of 17% in the manual shell shop foundry, thus around 45% saving in the rejection can be achieved by shell shop automation.

Table 6: Comparative study of manual and robotic shell shop

Defect	Rejection in manual shell shop	Rejection in Robotic shell shop
In clusion	4.0%	1%
Not Filling	3.0%	1.20%
Extra Metal	2.2%	0.10%
Shrinkage	2.0%	1.20%
Sub Total	**11.2%**	**3.5%**

4.1 Cycle time Reduction:- better design and movements of conveyor loops causes improved and well controlled proper air circulation from all the angles. This has helped to reduce the drying time from 8 hours minimum to 4 hours thus reduces cycle time from 4-6 days to 2-3 days.

4.2 Yield Improvement: -The mould carrying capacity constraint of the operators has been eliminated to greater extent in robotic layout. The patterns number per mould has been increased by average 27% - 32 %, which has helped to improve the metal yield.

4.3 Yield Improvement: - Use of robotics offers improvement in yield (from 29 % to 38 %) by producing shelling for heavy casting and designing larger mould. So, the mould carrying capacity constraint of the operators has been eliminated to greater extent, so the patterns number per mould has been increased by average 27% - 32 %, which has helped to improve the metal yield.

4.4 Productivity: - The hanger carry 6-8 moulds at a time and each mould is having 27% to 32% higher number of castings per mould, Hence the productivity has improved. The other reason for improvement in the productivity is that in robotic operation the hard work of the operator has reduced to only loading and unloading of the moulds on the hangers which is off line activity, hence labour fatigue does not arise. The mould breakages and the loss of castings due to handling damage has also minimised to improve the efficiency of the line.

5 CONCLUSION

Use of robot coupled with the conveyor is recommended due to multiple benefits such as reduced fatigue of worker, cycle time reduction, uniform coating, high yield etc. offered for improvements of the plant efficiency and reduce the operating losses. Thus, enhance the productivity of foundry industry. As the cost of the automation will reduce in the future, more and more similar implementation of process automation in other areas like wax assembly, foundry shop for metal pouring, and post casting operation can be economically feasible. Still the present cost criteria deprive small foundries the use of automation and robotics.

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