EFFECT OF PROCESS PARAMETERS ON MECHANICAL PROPERTIES OF THE INVESTMENT CASTINGS PRODUCED BY USING EXPANDABLE POLYSTYRENE PATTERN

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ABSTRACT

The present study is concerned with the investigation of mechanical properties of A713 alloy castings produced by investment casting process using expandable polystyrene as the pattern material and the plaster of paris as the mould material. Experiments were conducted as per Taguchi's L_9 orthogonal array. Castings were made under the constraint of different process parameters like mould firing temperature, pouring temperature, firing time and mixing of silica sand of different grain fineness numbers to investigate their effects on the surface hardness, impact strength and tensile strength of the final castings. The variations in the trend of the aforesaid mechanical properties were observed and it was deduced out that high mould firing temperature, higher pouring temperature, maximum firing time and high grain fineness number significantly reduce the mechanical properties of A713 alloy castings produced by the above process.

KEYWORDS

Investment casting, Expandable polystyrene pattern, Plaster of Paris.

1. INTRODUCTION

Investment casting is known for its quality castings rendering good surface finish and other desirable mechanical properties. The investment casting process involves the production of engineering castings using an expandable pattern [8]. The principle can be traced back to 5000 BC [9]. Investment casting is also known for producing the intricate details and high dimensional accuracy. Castings are replicated from the precise pattern and transmitted in turn to the castings. Investment casting allows dimensionally accurate components to be produced and is a cheaper alternative than forging and machining since waste material is kept to a minimum [2]. The investment casting process has increasingly been used to produce components for the aerospace industry and it has been particularly successful for the production of single crystal turbine blades [8,11,12]. Where on one hand the aforesaid advantages are obtained, there on the other hand it also hampers the casting process in terms of time required for the preparation of mould as well as requirement of skilled labor. The present work introduces expandable polystyrene as the pattern material. The inspiration of using polystyrene is taken from evaporative pattern casting methods using it as a pattern material [16]. In the present investigation a new method involving the elimination of polystyrene by acetone has been introduced. The present investigation also aims at making process as economical as possible by involving Plaster of Paris in the form of a mould material. Nine castings were prepared by taking Al-Zinc alloy (A713 alloy) and the effects of various parameters have been studied. A special designing of the pattern and the sprue has been done to form the plaster mould. The effect of different parameters like pouring temperature of the metal alloy, firing temperature, firing time and silica sand of different grain fineness numbers have been studied at three different levels. The effects of the aforesaid parameters on the selected mechanical properties like hardness, impact strength and tensile strength have been studied by using Taguchi method of design of experiments.

Barnett [1] found that refractory coating plays an important role in the ceramic shell investment casting. It provides refractory protection to ensure no metal penetration and smooth surface of shell mould. Jones and Marquis [2] concluded that the coating materials for ceramic shell investment casting moulds fall in three major categories: binders and catalyst, refractory fillers and additives. Each category has specific characteristics and purpose in forming the complete ceramic mould. The binders are of two types: alcohol based and water based. The alcohol based binder is ethyl silicate. Ethyl silicate slurries have relatively short life and must be discarded if they are not used within some definite time. The most commonly used water based binder is colloidal silica which is an aqueous suspension of amorphous silica. McGuire [3] found that fused silica has an extremely low coefficient of thermal expansion and can therefore be used to produce a dimensionally stable ceramic mould. Fused silica is a non-reactive filler and is easier to remove after casting in the knockout and cleanup operations. Fused silica also has good thermal shock resistance and is dimensionally very stable. Cui and Yang [4] presented a paper which explains that surface finish will be an important characteristic of the casting for that great attention must be given to the nature of the ceramic filler. Stability in handling of the cluster during coating and dewaxing and the specific gas permeability and removal behavior is the demand of ceramic shell investment casting. Jones et al. [5] concluded that if the refractory coating slurry is not allowed to drain uniformly, the pattern assembly may have irregular thickness which may affect its strength. Jones and Yuan [6] found that a weakened ceramic shell structure can lower the quality of an investment casting. The strength of a ceramic shell mould is a function of such factors as: mould material, shell build-up procedure, and firing procedure. Yuan et al. [7] presented a paper which explains the fiber modified ceramic shell. Fiber reinforced ceramic has a lower green strength than the polymer modified system. Although the polymer modified system exhibits a higher strength in the green dry stage, in practice, moulds produced with fiber additions are less susceptible to autoclave cracking. Li *et al.* [14] presented a paper which explain the influence of shell preheat temperature, pouring temperature and melt hydrogen content on the micro porosity and mechanical properties of the cast patterns. They concluded that the shell preheats temperature and the hydrogen content is the important process variables determining the amount of micro porosity in the investment casting. The porosity is increased by increasing the shell preheat temperature and hydrogen content. The low pouring temperature generally produces high mechanical properties. Baumeisth et al. [15] presented a paper which explains the influence of casting parameters on the micro structures and the mechanical properties of extremely small parts produced by micro castings. He concluded that for the specimen edges become sharper with increasing mould temperature. High mould temperature also results in the transfer of extremely fine details such as cracks and other surface defects from the mould on to the cast part. At a moderate these undesirable fine details are not critical thus making this temperature optimum for casting.

In the present investigation the different process parameters comprising of silica sand with different mesh numbers of silica sand, firing temperature, firing time and the pouring temperature have been taken into account to study their effects on the surface hardness, tensile strength and the impact strength of the castings.

2. EXPERIMENTATION

This section comprises of material selection for the mould and the aluminum alloy to be casted by investment casting using expandable polystyrene pattern. This section also throws light on the basis upon which the selection of different process parameters to be varied during the experimentation is done. Shell preheat temperature, pouring temperature and melt hydrogen content are the important process variables influencing the mechanical properties of the cast patterns [14]. The different stages adopted in the preparation of the mould and obtaining the final casting have been discussed.

Material selection for mould

Plaster of Paris has been used as the slurry to be coated over the polystyrene pattern which latter solidifies to form the mould material. Plaster of Paris is considered to be one of the best moulding materials rendering castings with the required dimensional tolerance and average surface finish. Major drawback of the slurry material is that it has got low or negligible permeability and also is a bad conductor of heat. In the present work 40 percent of silica sand by weight has been mixed to the 60 percent plaster of Paris by weight so as to increase its permeability. The silica sand of different mesh numbers like AFS No.45, AFS No. 60 and AFS No.100 has been taken in the present investigation.

Material selection for pattern

In the present investigation expandable polystyrene is adopted as the pattern material. Acetone, a ketone group of organic chemicals is used to dissolve the pattern and hence leaving behind a cavity to be filled by the molten alloy. This way the mould material and the pattern are the two things invested in making the final castings. The advantages of using expandable polystyrene as the pattern material are based upon the fact that any desired shape can be obtained easily and is also readily available at an economical price.

Material selection for alloy

In the present investigation A713 aluminum alloy has been taken to make the castings. A713 alloy comprises copper (0.1-1.0%), magnesium (0.2-0.5%), zinc (7.0-8.0%) and aluminum as the balance [17]. It is a high strength and low weight alloy used in aerospace engineering application. Owing to their good corrosion properties, high specific strength and low costs for shape forming, cast aluminum alloys are wised used in engineering applications, such as engines for vehicles, helicopters and fan hubs, etc. Due to its above features it could also be used in making engine blocks and other automotive parts [17].

2.1 Experimental process

Present work has gone through different stages and each successive stage has been obtained by implementing modifications in their preceding stages respectively. In the preliminary stage the castings were made in the moulds of plaster of paris without having silica sand content. This resulted in the castings with good surface finish but considerable porosity due to negligible permeability of the mould. Permeability of the shell is the most important factor, with most investment shells having a minimum of 30% open porosity in the structure [13].

First stage:-

A vertical gating system was prepared comprising of sprue and a pattern. This would render process simpler. Six layers of slurry comprising of plaster of paris and silica sand were made over the pattern. Acetone was dropped from sprue. The brown layer resembles slurry coated over the pattern shown in blue color. It was observed that as the acetone proceeded further, it went on dissolving the expandable polystyrene pattern and hence forming a full mould cavity. This cavity was ought to be filled by the molten alloy. Later when this mould was broken before making casting, it was observed that a thin but a hard layer of a product formed inside the mould cavity due to dissolving of polystyrene in acetone. This would have the ad

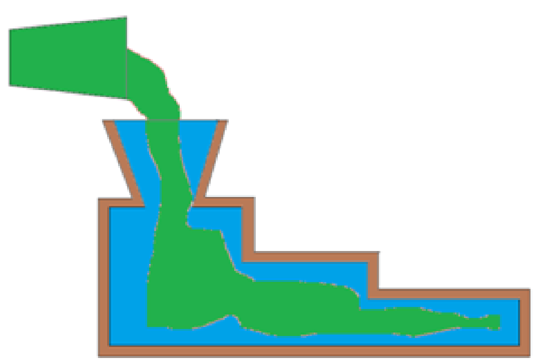

Fig. 1 Acetone dropped over the pattern coated with Plaster of Paris

Second stage:-

The pattern as shown in Fig.1 was divided into two halves. Slurry layers were coated over the polystyrene pattern as shown in Fig.2.

Now acetone was used to dissolve the polystyrene pattern from the two halves and thus form the mould cavity. The hard thin layer thus obtained was mechanically peeled out and the two parts were recombined followed by coating of three layers of slurry system coated over it. Now the molten metal was poured to form the final castings after the moulds were dried enough by preheating.

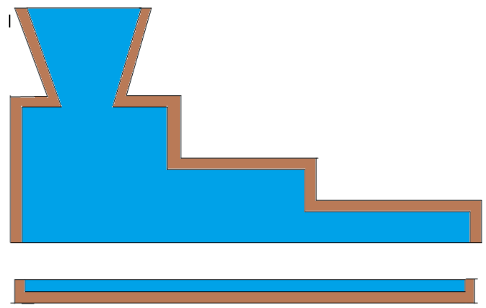

Fig. 2 Two parts of pattern with coating

Third stage:-

Method consisting of using an optimized quantity of acetone was deduced out in the third stage. This rendered process more economical and safe as acetone is also known for its hazardous effects. A glass syringe was used to inject the acetone in the mould consisting of expandable polystyrene pattern. Through experiment it was found out that 2 ml of acetone dissolves 1cm^3 of the expandable polystyrene leaving behind a messy moist layer of polystyrene which could be latter peeled out. Hence a required amount of acetone for a particular volume of pattern could be easily found out. The glass syringe facilitated the way of injecting acetone to the intricate parts of the mould as well.

2.2 Experimental design

Selection of orthogonal array

Taguchi recommends Orthogonal Array (OA) for designing the experiments. OA's are generalized Graeco-Latin squares. To design an experiment is to select the most suitable OA and to assign the parameters and interactions of interest to the appropriate columns [18]. The use of linear graphs and triangular tables suggested by Taguchi makes the assignment of parameters simple. In the Taguchi method the results of the experiments are analyzed to achieve one or more of the following objectives;

- To establish the best or the optimum condition for a product or process
- To estimate the contribution of individual parameters and interactions
- To estimate the response under the optimum condition
- Four process parameters have been selected as potentially important in affecting the mechanical properties of the casting. The selected process parameters and their values at different levels are given in Table 1.

Table 1: Levels of process parameters

Process parameters	**Level 1**	**Level 2**	**Level 3**
Silica sand AFS No.(A)	45	60	100
Preheat temperature (B)	200^0C	250^0C	300^0C
Pouring temperature(C)	750^0C	700^0C	670^0C
Preheat time (D)	3 hrs	6 hrs	9 hrs

The selection of a particular orthogonal array is based on the number of levels of various factors.

Here, to conduct the experiments 4 factors each at 3 levels were selected. Now the Degree of Freedom (DOF) can be calculated by the formula as given below [18].

$(DOF)_R = P*(L – 1)$

$(DOF)_R$ = degree's of freedom
P = number of factors
L = number of levels
$(DOF)_R = 4(3 – 1) = 8$

However, total DOF of the orthogonal array (OA) should be greater than or equal to the total DOF required for the experiment. Thus L_9 orthogonal array was selected to make the further experiments which are shown in Table 2 [18].

Table 2: L9 Orthogonal array

Expt. No.	A	B	C	D
1	1	1	1	1
2	1	2	2	2
3	1	3	3	3
4	2	1	2	3
5	2	2	3	1
6	2	3	1	2
7	3	1	3	2
8	3	2	1	3
9	3	3	2	1

3. RESULTS

The effect of various process parameters taken on selected mechanical properties of A713 aluminum alloy castings has been discussed in this section. The experiments were conducted using the L_9 orthogonal array [18]. The L9 OA with 4 factors, 3 levels and its responses are shown in the Table 3.

Table 3: Experimental data

Expt. No.	A	B	C	D	Hardness (BHN)	Impact Strength (Joule)	Tensile strength (N/mm^{2})
1	45	200	750	3	65.66	13.7	167.13
2	45	250	700	6	69.23	13.6	171.13
3	45	300	670	9	66.72	13.1	168.82
4	60	200	700	9	65.34	12.9	168.64
5	60	250	670	3	64.62	12.1	167.82
6	60	300	750	6	60.18	11.5	163.10
7	100	200	670	6	63.26	9.6	166.96
8	100	250	750	9	59.87	8.4	157.12
9	100	300	700	3	55.47	8.2	161.63

The mean value of hardness obtained at each level of the respective process parameters have been shown in Table 4.

Table 4: Average values [Response: Hardness]

P	L1	L2	L3
A	67.20	63.38	59.53
B	64.75	64.57	60.79
C	61.90	63.34	64.86
D	61.91	64.22	63.97

3.1 Effect of process parameters on hardness of castings

Fig. 3-6 show the variation of hardness with change in the levels of grain fineness number (process parameter 'A'), mould preheating temperature (process parameter 'B'), pouring temperature (process parameter 'C') and preheating time (process parameter 'D') respectively. From these graphs it can be observed that hardness of the castings varies significantly with the change in the levels of the respective process parameters. The hardness decreases with the increase in the grain fineness number and preheating temperature. It considerably increases with the decrease in the pouring temperature. Hardness shows the increasing and decreasing trend with the increase in the mould preheating time.

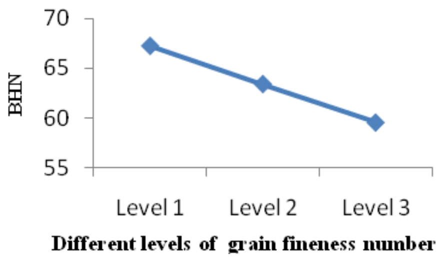

Fig. 3 Variation of hardness with the levels of process parameter 'A'

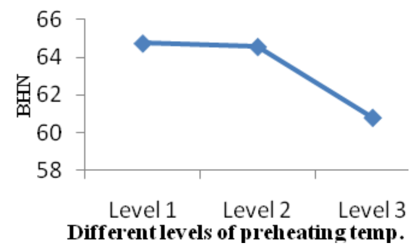

Fig. 4 Variation of hardness with the levels of process parameter 'B'

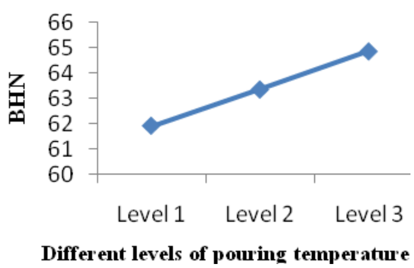

Fig. 5 Variation of hardness with the levels of process parameter 'C'

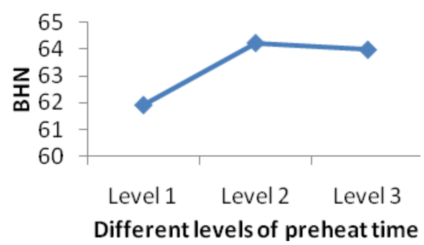

Fig. 6 Variation of hardness with the levels of process parameter 'D'

The mean value of impact strength obtained at each level of the respective process parameters have been shown in Table 5.

Table 5: Average values [Response: Impact strength]

P	L1	L2	L3
A	13.46	12.16	8.73
B	12.06	11.36	10.93
C	11.20	11.56	11.60
D	11.33	11.56	11.46

3.2 Effect of process parameters on impact strength of castings

Fig. 7-10 show the variation of impact strength with change in the levels of grain fineness number (process parameter 'A'), mould preheating temperature (process parameter 'B'), pouring temperature (process parameter 'C') and preheating time (process parameter 'D') respectively. The graphs show the variation in the impact strength of the castings with the change in the levels of the aforesaid process parameters. The impact strength declines down with the increase in the grain fineness number and preheating temperature. It increases with the decrease in the pouring temperature. Impact strength first increases and then decreases with the increase in the mould preheating time.

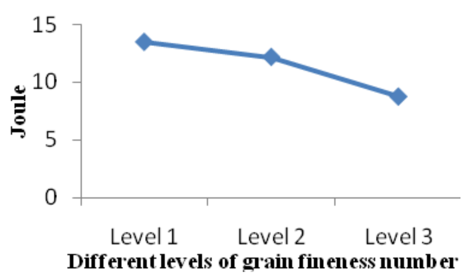

Fig. 7 Variation of impact strength with the levels of process parameter 'A'

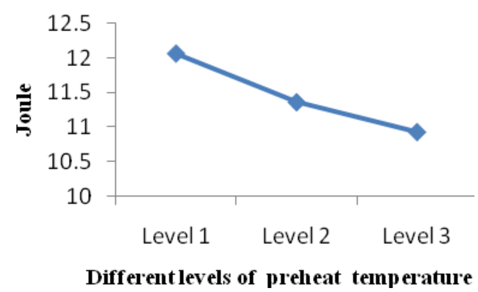

Fig. 8 Variation of impact strength with the levels of process parameter 'B'

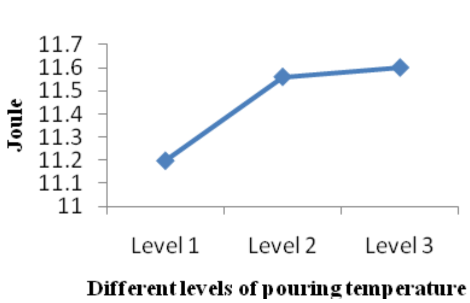

Fig. 9 Variation of impact strength with the levels of process parameter 'C'

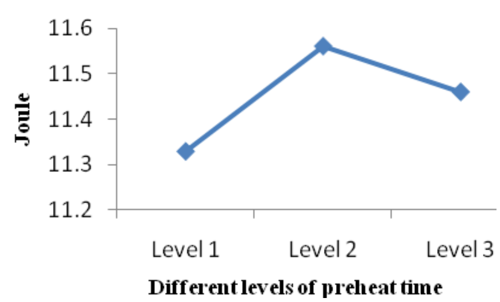

Fig. 10 Variation of impact strength with the levels of process parameter 'D'

The mean value of tensile strength obtained at each level of the respective process parameters have been shown in Table 6.

Table 6: Average values [Response: Tensile strength]

P	L1	L2	L3
A	169.02	166.52	161.90
B	167.57	165.35	164.51
C	162.44	167.13	167.86
D	165.52	167.06	164.86

3.3 Effect of process parameters on tensile strength of castings

Fig. 11-14 show the variation of tensile strength with change in the levels of grain fineness number (process parameter 'A'), mould preheating temperature (process parameter 'B'), pouring temperature (process parameter 'C') and preheating time (process parameter 'D') respectively. The graphs reveal the considerable variation in the tensile strength of the castings with the change in the levels of the respective process parameters. The tensile strength decreases with the increase in the grain fineness number and preheating temperature. It increases with the decrease in the pouring temperature. Tensile strength graph shows the increasing and decreasing trend with the increase in the mould preheating time.

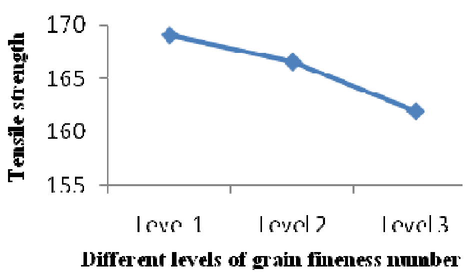

Fig. 11 Variation of tensile strength with the levels of process parameter 'A'

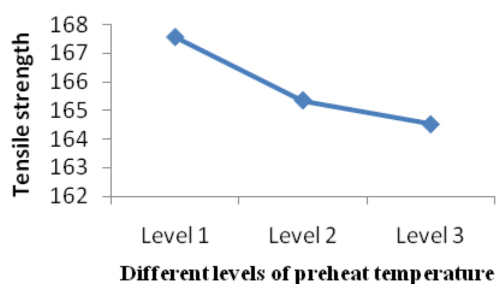

Fig. 12 Variation of tensile strength with the levels of process parameter 'B'

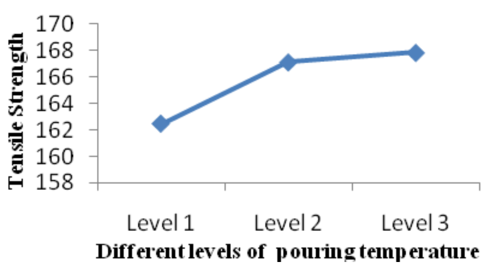

Fig. 13 Variation of tensile strength with the levels of process parameter 'C'

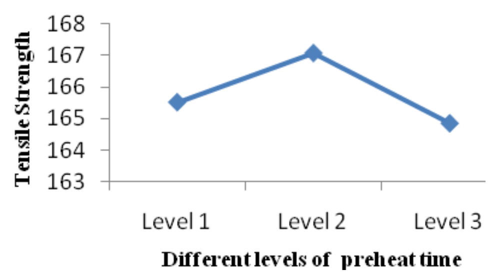

Fig. 14 Variation of tensile strength with the levels of process parameter 'D'

4. DISCUSSION

It is clear from the figures 3, 7 and 11 that hardness, impact strength and the tensile strength decrease with the increase in the grain fineness number of the sand. This may be attributed to the reason that large amount of fines are available with a sand of high AFS number. These fines settle during coating and shell building, resulting in reduced voids at the shell mould surface layers. Due to the reduced voids in the sand mixtures, there is reduction in the radiative heat transfer coefficient. Thus the solidification rate reduces, which in turn reduces the tensile strength, impact strength and hardness of the castings. The permeability of the ceramic shell mould has an important influence on the mould filling [6]. Decrease in the total permeability and increase of excessive strength in the shell is observed due to increase in the grain fineness number which further results in decrease in the mechanical properties.

It is clear from the figures 4, 8 and 12 that the aforesaid mechanical properties decrease with the increase in the firing temperature. Porosity is increased by increasing the shell preheat temperature and hydrogen content which further hampers the mechanical properties [14]. This may also be attributed to the reason that solidification time reduces due to the high temperature gradient and hence there is reduction in radiative heat transfer coefficient which in turn reduces the tensile strength, impact strength and hardness of the final castings thus obtained.

The higher temperature of the liquid metal provides better feeding of the liquid metal at the inter-dendritic cavities. At the same time, solubility of hydrogen gas in the liquid metal increases at the higher pouring temperature of the liquid metal. The dissolved hydrogen gas comes out of the molten metal during solidification due to its lower solubility at lower temperatures. Hydrogen content in the melt increases the porosity [14]. Part of the gases may get entrapped which leads to increases porosity in the castings. Pouring temperature significantly reduces the mechanical properties as shown in the figures 5, 9, 13. This reduction may be due to the development of high thermal gradients which slows the time of solidification. The mechanical properties are improved by decreasing the pouring and mould pre heat temperatures [14].

It is clear from the figures 6, 10 and 14 that the aforesaid mechanical properties shows the increasing and decreasing trend with the increase in the firing time. With the increase in the firing time the moulds attain pores due to burn out of some ceramic materials as well as due to some loss of moisture. But with the increase in the firing time, a higher thermal gradient is obtained resulting in slow cooling hence decreasing the radiative heat transfer coefficient and hence reducing the mechanical properties.

5. CONCLUSIONS

The work concluded on the influence of the aforesaid process parameters on the mechanical properties of A713 alloy castings. Shell preheat temperature, pouring temperature, the grain fineness number and the preheating time are the important process parameters affecting the mechanical properties of A713 alloy castings.

The hardness, impact strength and the tensile strength decrease with the increase in the grain fineness number of the sand due to the increase in the voids among the grains resulting in the increase in overall permeability and sufficient strength to the mould. The strength should be sufficient but not maximum as it hampers the mechanical properties.

The hardness, impact strength and the tensile strength decrease with the increase in the mould pre heat temperature. The time of solidification increases followed by reduction in the radiative heat transfer coefficient resulting in decrease of the mechanical properties.

The hardness, impact strength and the tensile strength decrease with the increase in the pouring temperature of the molten alloy. Increase in the pouring temperature results in the increase of the melt hydrogen content followed by picking up the moisture in the form of vapours from the mould. The combined effect of these causes considerable porosity resulting in poor castings and further hampering the aforesaid mechanical properties.

The hardness, impact strength and the tensile strength show the increasing and decreasing trends with the variation in preheating time. With the increase in preheating time the moisture content of the shell decreases and hence the porosity is considerably reduced to some extent but increases due to the increase in the shell preheat temperature and hence hampering the mechanical properties.

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