Optimization of process parameters of A-359 aluminium alloy in EPS-assisted-investment casting process using Taguchi method

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Abstract. The purpose of this research is to optimize the process parameters such as pouring temperature, pouring time and the thickness of coating using Taguchi mod in expandable polystyrene assisted investment casting process. In this paper, zircon flour and mullite sand with potassium silicate binder and coarse fused-silica sand stucco are used as coating materials. Problems like cracking, breaking, bending, expanding and distending in shell are eliminated by preheating the shell and slowly rise in temperature, during foam removal process. For maximum impact strength, the optimum values of process parameters- pouring temperature, pouring time and thickness of coating layers are 750°C, 15 seconds and 5 mm respectively.

Keywords: Expandable Polystyrene Pattern, A-359 Aluminium Alloy, Pouring temperature, Pouring time and Thickness of coating layers, Taguchi Method.

1. Introduction

In present time, the dimensional accuracy and surface finish of casted complex shape products have become a critical issue to reduce machining cost. So, different types of casting processes have been introduced. In this row, two types of castings are preferred named as evaporative pattern casting (EPC) and investment casting process. But evaporative pattern casting is facing problems of pin holes, porosity, ash content etc. in castings [1-2]. In investment casting process, these defects can be reduced. Generally, wax patterns are used in investment casting. But due to low softening point, the change in shape of wax pattern takes place. Another problem is to handle the big and complex shapes of wax pattern [3-4]. To remove these problems, there is a great opportunity in investment casting to use Expandable Polystyrene pattern, instead of wax pattern. This hybrid casting process is called EPS Assisted Investment Casting Process [5-6]. To achieve good characteristics of casting, Al-Si system of aluminium alloys is preferred. The range of Si may vary 4% to 13%. In this research work, A-359 aluminium alloy has been selected because of it has low melting point, high strength, good fluidity, low ductility, decreased corrosion resistance and surface roughness, good grain structure and ability to increase the strength by heat treatment [6]. The composition of A-359 is shown in table-1.
Table 1. Composition of A-359 Aluminum Alloy

|   | Si   | Mn   | Mg   | Ti  | Fe  | Cu  | Zn  | Al |
|---|------|------|------|-----|-----|-----|-----|----|
|   | 9%   | 0.10%| 0.5% | 0.2%| 0.2%| 0.2%| 0.1%|    |

2. Literature review

Kumar et al (2007) investigated the effect of density of EPS pattern and metal pour temperature on surface finish of castings in EPC. They concluded that the pattern having the low density was required to generate the less amount of gas in the evaporation of the pattern. The gas generation rate should be less than it can vent, otherwise castings will be defective. More gases will be generated by high density EPS pattern in which bead size is small [7]. Zhao et al (2011) compared the properties such as composition, elastic modulus and decomposition temperature of Expandable Polystyrene (EPS), Stereo-lithography Apparatus (SLA) and Foam pattern material (FOPAT) in casting process. They concluded that the EPS and SLA patterns degraded more readily than the FOPAT pattern in both air and N2 atmospheres. The EPS, SLA and FOPAT patterns were decomposed completely at 450°C, 600 °C and 680 °C, respectively at both atmospheres [8]. Prasad et al (2003) determined the accuracy of castings and optimized the injection variables used in manufacturing of wax pattern by injection moulding. They found the dimensional errors occurred are a reduction of 0.2–0.4% in dimension [9]. Jin et al (2017) summarized the properties of coating materials like alumina and zircon and stucco material like fused silica and factory granules in investment casting using wax pattern. They analyzed the defects in ceramic shell due to bending, linear expansion and shrink because of thermal expansivity of refractory, contents of impurities with low melting points, grain size, roasting temperature, soaking time, ambient humidity, uniformity of composition, uniformity of thickness, uniformity of drying, uniformity of geometric structure [10]. Tiwary et al (2015) pointed out the effects of Fused Deposition Modelling process variables and various methods of chemical treatment on surface finish of Acrylonitrile Butadiene Styrene (ABS) patterns in conventional investment casting using Taguchi method. [11]. Jones and Yuan (2003) optimized the properties of shells and explored the various methods for the improvement of shell properties in conventional investment casting process [12]. Sidhu et al (2008) studied the influence of primary coating slurry variables on the plate weight in ceramic shell based investment casting process. They optimized the parameters by using Taguchi’s method with zircon sand and fused-silica sand in powder form based slurries. They also used stucco material as coarse fused-silica sand [13]. Liu et al (2015) observed that an average shrinkage of 0.65 % percent magnitude has been obtained by the constrained dimensions and for unconstrained dimensions; it is 2.85 % [14]. Bhati et al (2017) analyzed the influence of density and viscosity of coating slurry on the strength of shells generated by EPS Assisted Investment Casting Process. They concluded the optimum density and viscosity are 1.96 gm/cm3 and 8000 cp at 42.8% torque [15]. Carneiro et al (2019) represented additive manufacturing in wax pattern based investment casting with the help of vacuum assist pouring for thin-rib. They found the value of minimum temperatures for the mold and for the casting are 250 °C and 700°C respectively [16]. Xu et al (2019) investigated the microstructure and mechanical properties in ceramic shell based investment casting for turbine blades Alumina was used for ceramic shell material. They have taken shell thickness as 8.8 mm, with sintering at 1000 °C for 60 min. and dewaxed in a steam autoclave [17].

3. Experimental procedure

The experimental procedure of EPS Assisted Investment Casting Process is shown in figure 1.

3.1 Fabrication of Pattern: In this Hybrid casting process, Expendable Polystyrene (EPS) pattern is used. The density of EPS pattern is taken as 17 kg/m³. Hot wire method is used to cut the EPS patterns from polystyrene sheet. The EPS pattern is shown in figure 2.
3.2 Preparation of Coating Slurry: The coating material is selected based on the factors such as density, melting point, linear expansion coefficient, chemical composition, cost, etc. In order to obtain smooth ceramic shell surface, a certain amount of fine grade powder is needed. Due to following properties (shown in table 2), zircon flour and mullite are selected as coating materials.

Table 2. Properties of Mullite and Zircon Flour

| Coating Materials | Density (gm/cc) | Hardness (Kg/mm²) | Maximum Use Temperature (°C) | Thermal Conductivity (W/m•°K) | Coefficient of Thermal Expansion (10⁻⁶/°C) |
|-------------------|----------------|-------------------|-------------------------------|------------------------------|--------------------------------------|
| Mullite           | 2.8            | 1070              | 1650                          | 6                            | 5.4                                  |
| Zircon            | 6              | 1300              | 1500                          | 2                            | 10.3                                 |

Potassium silicate is used as binder. The best composition of the mulite, zircon flour and potassium silicate is:
- Zircon Flour (5 %) + Mullite (35 %) + Potassium Silicate (60 %) for primary coating [18],
- Mullite (40 %) + Potassium Silicate (60 %) for secondary coating [18],
- Coarse fused-silica sand as stucco [13].

Slurry of different combination of coating materials is prepared with the help of mechanical stirrer. Combinations of different coating materials have been rotated at 1400 rpm for 10 minutes. The density and viscosity of this slurry are 1.96 gm/cm³ and 5700 cp respectively [18].
3.3 Primary, Stucco and Secondary Coating on EPS Pattern: After the preparation of slurry, pattern is dipped into the primary slurry. Then coarse fused-silica sand is used as stucco material for support to secondary coat. After being dry, secondary coating takes place on the pattern.

3.4 Foam Removal Process: Shell has been created by decomposition of expandable polystyrene pattern with the application of heat. For this purpose, muffle furnace is used. As coated foam pattern is placed in the furnace, the foam starts to melt. At high temperature, foam starts to evaporate. After fully decomposition of foam, cavity creates. If coated patterns are kept in a furnace at high temperature directly, then heating rate will be fast and forms cracking, breaking, bending, expanding and distending in shell. This problem can be minimized with the help of preheating the shell and slowly rise in temperature. Firstly, shell is preheated at 80°C for 30 minutes. After preheating, shell is heated till temperature rises up to 120°C at a rate of 4°C/ minute. Shells are heated at constant temperature (120°C) for 20 minutes. Again heated till the temperature rises up to 160°C at a rate of 4°C/ minute for 10 minutes and then heated at constant temperature for 20 minutes [6].

3.5 All shells are placed in a silica sand filled moulding box. Loose sand is compacted with the help of vibrator and vacuum pump. A-359 aluminium alloy has been melted in a muffle furnace at different temperature ranges. Melted aluminium alloy is directly poured in shells. After solidification of all filled shells are removed from moulding box. The ceramic coating has been removed from castings [18].

3.6 Process Parameters: The following process parameters affect the impact strength in Expandable Polystyrene Assisted Investment Casting Process.

- Pouring Temperature
- Poring Time
- Amount of Stucco Material (gm/cm²)
- Grain Fineness Number (GFN) of Molding Sand
- Compactness of Molding Sand
- Thickness of Coating Layers
- Density of Pattern
- Viscosity of Coating Slurry
- Heat Transfer Rate during Foam Removal Process

In this research work, main three parameters (pouring temperature, pouring time and the thickness of coating) are selected at three levels are shown in table-3. The remaining parameters are fixed. The amount of stucco sand, grain fineness number (GFN) of molding sand, density of pattern, density and viscosity of coating slurry are 5 gm per cm² surface area of shell, 100, 17 kg/m³, 1.96 kg/m³ and 5700 cp respectively.

| Process Parameters             | Level-1 | Level-2 | Level-3 |
|-------------------------------|---------|---------|---------|
| Pouring Temperature (°C)      | 700     | 750     | 800     |
| Pouring Time (Seconds)        | 5       | 10      | 20      |
| Thickness of Coating Layers (mm) | 2     | 5       | 8       |

3.7 Impact Testing: In this paper, nine experiments are conducted for different process variables and their different levels as shown in table-4. From these nine castings, nine specimens are prepared for impact strength testing as shown in figure 3. The results are discussed in table 4.
Figure 3. Specimens of Impact Strength Testing

4. Result and discussion

4.1. Taguchi’s Philosophy-

4.1.1. Selection of Orthogonal Array (OA): For Design of Experiments (DOE), Taguchi recommends orthogonal array (OA). The objectives of DOE in Taguchi method are following -

- To estimate the participation of individual variables with their interactions.
- To establish the optimum value of process variables for any process.
- To estimate the outcomes under the optimum condition.

In this research, three levels of three parameters are selected. Degree of Freedom (DOF) is calculated as-

\[(DOF) = P(L - 1)\]  \hspace{1cm} (1)

where (DOF) = degree of freedom, P = number of factors and L = number of levels.

Here, P=L=3; \hspace{1cm} so \hspace{1cm} DOF=3(3-1)=6.

Thus, selected L_9 orthogonal array is given in Table-4. The S/N ratio characteristics - Larger Value of Impact Strength is better-

\[S/N = -10 \times \log \left[ \frac{1}{n} \sum \frac{1}{Y_i} \right] \]  \hspace{1cm} (2)

Table 4. Taguchi Design Matrix for Impact Strength

| Sample No. | Pouring Temperature (°C) | Pouring Time (Seconds) | Thickness of Coating Layers (mm) | Impact Strength (Joule) | S/N Ratio |
|------------|--------------------------|------------------------|---------------------------------|-------------------------|-----------|
| 1          | 700                      | 5                      | 2                               | 8.6                     | 18.6900   |
| 2          | 700                      | 15                     | 5                               | 9.0                     | 19.0849   |
| 3          | 700                      | 25                     | 8                               | 8.2                     | 18.2763   |
| 4          | 750                      | 5                      | 5                               | 8.5                     | 18.5884   |
| 5          | 750                      | 15                     | 8                               | 8.4                     | 18.4856   |
| 6          | 750                      | 25                     | 2                               | 8.2                     | 18.2763   |
| 7          | 800                      | 5                      | 8                               | 7.9                     | 17.9525   |
| 8          | 800                      | 15                     | 2                               | 8.3                     | 18.3816   |
| 9          | 800                      | 25                     | 5                               | 7.9                     | 17.9525   |

Average 8.33 18.4097
With the help of L9 OA, nine experiments have been performed and measured the impact strength as shown in table 4. Minitab 19 is used to generate Signal to noise (S/N) ratio of impact strength and raw data mean response are generated for all nine experiments. The response graph of S/N ratio is shown in figure 4. For impact strength larger is better.

Response table for S/N ratios represented the ranks of process parameters, shown in Table-5.

Table 5. Response Table for Signal to Noise (S/N) Ratios

| Level |
|-------|
| 1     |
| 2     |
| 3     |
| Delta |

| Pouring Temperature | Pouring Time | Coating Thickness |
|--------------------|--------------|-------------------|
| 18.68              | 18.41        | 18.45             |
| 18.45              | 18.65        | 18.54             |
| 18.10              | 18.17        | 18.24             |
| 0.59               | 0.48         | 0.30              |

**Rank**

| Rank |
|------|
| 1    |
| 2    |
| 3    |

Model Summary-

| S   | R-Sq  | R-Sq(adj) |
|-----|-------|-----------|
| 0.0542 | 99.43% | 97.71% |

![Main Effects Plot for SN ratios](image)

**Figure 4.** Response Graph for S/N Ratio

4.1.2 Effects of Process Parameters on Impact Strength:

By using Taguchi’s Method, the following effects of process parameters on impact strength are observed from figure 4 and table 5.

- Pouring temperature is the most affecting parameter and coating thickness is least affecting parameter on the basis of impact strength.
- At 700°C pouring temperature, impact strength is maximum. Also, as pouring temperature increases, impact strength decreases.
Impact strength is maximum when pouring time is 15 seconds. The impact strength is least at 25 seconds as pouring time.

Impact strength is maximum at 5 mm thickness of coating of shell. The impact strength is least at 2 mm as coating thickness of a shell.

### 4.1.3 Analysis of Variance (ANOVA):

To find the significance of the process parameters, it is required to achieve maximum value of the impact strength. So, analysis of variance is performed as shown in Table. The ANOVA is performed on S/N data as shown in Table-6.

**Table 6. Analysis of Variance for SN ratios**

| Source                | DF | Seq SS   | Adj SS   | Adj MS     | F     | P    |
|-----------------------|----|----------|----------|------------|-------|------|
| Pouring Temperature   | 2  | 0.52619  | 0.526191 | 0.263096   | 89.46 | 0.011|
| Pouring Time          | 2  | 0.34892  | 0.348922 | 0.174461   | 59.32 | 0.017|
| Coating Thickness     | 2  | 0.14545  | 0.145450 | 0.072725   | 24.73 | 0.039|
| Residual Error        | 2  | 0.00588  | 0.005882 | 0.002941   |       |      |
| **Total**             | 8  | 1.02645  |          |            |       |      |

where, DF- degree of freedom, SS- sum of square, MS- variance, F- variance ratio and p-significant factor (p ≤ 0.05).

### 4.1.4 Estimation of Output Characteristics:

The average value is being refers by mean response. The average values of impact strength were calculated and given in table 7.

**Table 7. Main effect on Impact Strength (raw data)**

| Process Parameters (Impact Strength) | Level | Pouring Temperature | Pouring Time | Coating Thickness |
|-------------------------------------|-------|---------------------|--------------|-------------------|
| Average Values                      | L₁    | 8.6                 | 8.33         | 8.37              |
|                                     | L₂    | 8.37                | 8.57         | 8.47              |
|                                     | L₃    | 8.03                | 8.1          | 8.17              |
| Main Effect                         | L₂ - L₁ | -0.23               | 0.23         | 0.1               |
| (Impact Strength)                   | L₃ - L₂ | -0.33               | -0.47        | -0.3              |
| Difference                          | (L₃ - L₂) - (L₂ - L₁) | -0.1         | -0.7          | -0.4              |

The process parameter levels of 1, 2, 3 are depicted as L₁, L₂, L₃. Average of mean effect is L₂-L₁ for the change in parameters corresponding to levels 1 to 2. Average of mean effect is L₃-L₂ for the change in parameters corresponding to levels 2 to 3.

On the basis on level of optimum process parameters, the optimal impact strength value has been forecasted. The optimum process variables and their level of optimization being prior opted as (1-2-2); 1 = at level 1, the optimum value of impact strength is obtained at pouring temperature and time at 700 °C. 2 = at level 2, the optimum value of impact strength is obtained at 15 seconds as pouring time and 5 mm coating thickness. The mean of characteristic of response can be calculated as

$$\mu_{IS} = IS_{A₃} + IS_{B₂} + IS_{C₂} - 2IS_{avg}$$

(3)

Where,

- ISavg = Overall mean impact strength = 8.33
- ISA₁ = Value of average impact strength for pouring temperature at level 1 factor= 8.6
- ISB₂ = Value of average impact strength for pouring time at level 2 factor = 8.57
- ISC₂ = Value of average impact strength for coating thickness at level 2 factor = 8.47

Hence,
µIS = 8.6+8.57+8.47-2×8.33 = 8.98

The 95% confidence intervals of confirmation experiments (CI_CE) can be calculated by using the equation as mentioned below.

\[ CI_{CE} = \sqrt{F_\alpha(1,f_e)V_e\left[\frac{1}{\eta} + \frac{1}{R}\right]} \]  

(4)

Where, error variance=V_e, F ratio \((F_\alpha(1,f_e))\) for the level of confidence i.e, \((1-\alpha)\) for degree of freedom 1 and \(f_e\) is error of DOF. Confidence level is “\(\alpha\)”. Effective number of replications (\(\eta\)) is calculated using equation,

\[ \eta = 1 + \frac{\text{DOF associated in estimate of mean response}}{N} \]  

(5)

Where, total number of results, \(N = 9\) (treatment = 3, reception = 3) and sample size for confirmation of experiments, \(R = 3\), Variance of error = 0.3333 , error DOF = 2 , \(F_{0.05}(1,2) = 18.91\), \(\alpha = 1 - 0.95 = 0.05\).

\[ CI_{CE} = \pm 2.04 \]

The predicted optimal range is:

\[ (\mu_{IS} - CI_{CE}) < \text{Impact Strength} < (\mu_{IS} + CI_{CE}) \]  

(6)

i.e. 6.94 < Impact Strength < 11.02

Here, it is observed that optimum parameters (700 °C as pouring temperature, 15 seconds as pouring time and 5 mm thickness of coating of shell) exist in L9 orthogonal table for sample no. 2 which has maximum impact strength equal to 9 Joule which lies between 6.94 Joule and 11.02 Joule. So, there is no need of confirmation test.

5. Conclusions

On the basis of this research work, it is concluded that the optimum process parameters- pouring temperature, pouring time and the thickness of coating of shell are 700°C, 15 seconds and 5 mm, respectively when the fixed parameters grain fineness number (GFN) of Moulding Sand, density of pattern, density and viscosity of coating slurry are 100, 17 kg/m3, 1.96 kg/m3 and 5700 cp respectively. Also, pouring temperature is the most affecting parameter and coating thickness is least affecting parameter on the basis of impact strength.

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