An Application of Analytical Hierarchy Process in Selection of Coating Material Composition in Lost Foam Casting Process

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Abstract. In modern industrial era, the dimensional accuracy and surface finish are two major criteria in the selection of casting process. To achieve this paradise, lost foam casting is one of the casting processes. In this casting process, the shell is made by removal of expandable polystyrene or foam pattern with the application of heat. During the foam decomposition process, many problems have been generated such as bending, expansion, distending and crack of the shell. These problems may be eliminated by selecting the optimum ratio of coating materials. In this research work, zircon and aluminium silicate refractory coating materials with sodium silicate binder have been used with different composition and prepared the four test samples from them. For selection of best shell material composition, analytical hierarchy process is used.

Keyword: Foam Pattern, Zircon, Alminium Silicate, Sodium silicate, Analytical Hierarchy Process

1. Introduction:
In automobile sectors, castings made of Aluminium and its alloys are extremely applicable because these are replacing the heavy forged steel and cast. It became very important to produce defect free aluminium castings without using secondary machining. Investment casting is one of the oldest casting processes. It is used for producing better dimensional accuracy of complex shape products. Another important process is Lost Foam Casting (LFC). In this process lost foam pattern is used. It is a cavity less and binder less process. With the help of this process, we can fabricate the automobile and IC engine components such as cylinder head, piston, connecting rod, brake shoes etc. as well as agriculture equipment \cite{1-2}.

The lost foam selected for LFC process have 92\% C and 8\% H. C6H5 benzene ring in lost foam is comparatively stable and −CH= CH2 chain tends to decompose first. The benzene ring remains in liquid phase and reacts with melt causing casting defects. Polymethylmethacrylate (PMMA) decomposed mostly into gas phase, like 80\% at 700° C while polystyrene only 40\% at 700 °C \cite{3-6}. Coating materials such as siliminite, quartz, aluminum silicate, zircon flour etc have been used by various researchers and the binder for cost effectiveness. Zircon and aluminium silicate have high density and viscosity, low dielectric constant, and pH value nearer to neutral refractory \cite{7-10}.

The selection of binding agent depends on the shape and size of particles of refractory materials so that the bonding and adhesive strength of particles and binders has been increased on the surface of foam pattern. Sodium silicate and potassium silicate with
water have been used as a solvent. The optimal density of ceramic slurry was 2000 kg/m³ [11-12]. Pattnaik et al. (2012) reviewed the different primary coating materials in investment casting process with wax pattern. They analysed the layer thickness of Ti–1100 casting and ZrO2 primary coating (38 μm) was higher than Y2O3 (Yttrium Oxide) primary coating (18 μm) [13]. Lu et al. (2018) analyzed the influences the firing time and firing temperature on the firing bonding strength of fibered reinforced ceramic shells in investment casting process. They have taken aluminium silicate and glass fibres as reinforced material. The maximum bending strength of reinforced shells has been achieved at 950 °C temperature and firing to 120 minutes [14]. Venkat et al. (2020) fabricated the ceramic shell for the blisk of low-pressure turbine rotor by using wax pattern-based investment casting process. They used aluminium silicate and zircon as coating material with cobalt aluminate [15]. The Analytical Hierarchy Process (AHP) is an important mathematical tool which is used to find the priorities of various decision options through pair-wise comparisons of decision elements with respect to common criteria [16-17].

Table 1. The Saaty Rating Scale

| Intensity | Definition                     | Description                                                                 |
|-----------|--------------------------------|-----------------------------------------------------------------------------|
| 1.        | Equal importance              | Two factors contribute equally to the objective                             |
| 3.        | Moderate importance of one over another | Experience and judgment favour one factor over another                      |
| 5.        | Essential or strong Importance | Experience and judgment strongly favour one factor over another             |
| 7.        | Very strong importance        | An factor is strongly favoured and its dominance demonstrated in practice  |
| 9.        | Extreme importance            | The evidence of favouring one factor over another is of the highest possible order of affirmation |
| 2, 4, 6, 8| Intermediate values,           | When compromise is needed                                                   |

Usually, the patterns are made up of wax in investment casting. But wax has low melting point and also, it is not easy to handle the big and complex shapes of wax pattern. These problems have been eliminated in lost foam casting process [18]. The different combinations of coating materials (zircon and aluminium silicate with sodium silicate or potassium silicate binder) have been optimized by using Analytical Hierarchy Process (AHP).

1. **Selection of Materials**

a) **Coating materials:** -
In this work, zircon and aluminium silicate sand are used as coating materials, in different ratio and composition. Sodium silicate is used as binder. The following compositions of refractory powder have been selected for primary coating.

Sample: 1 – Zircon (0 %) + Aluminium silicate (50 %) + Sodium Silicate (50%)  
Sample: 2 – Zircon (20 %) + Aluminium silicate (30 %) + Sodium Silicate (50%)  
Sample: 3 – Zircon (30 %) + Aluminium silicate (20 %) + Sodium Silicate (50%)  
Sample: 4 – Zircon (50 %) + Aluminium silicate (0 %) + Sodium Silicate (50%)  

For secondary coating compositions, aluminium silicate (50 %) with Sodium Silicate (50%) is selected.

b) Pattern Material:-
In lost foam casting process, lost foam patterns are used. The density of lost foam pattern is 20 kg/m3. For this analysis, step shaped pattern has been shown in Figure 1.

II. Methods

c) Slurry Preparation: Slurry of different composition of refractory powder materials has been uniformly mixed and made through mechanical stir. Compositions of coating materials have stirred at 1000 rpm for 15 minutes.

d) Coating on lost foam pattern: After the preparation of primary and secondary slurries, lost foam pattern has been dipped in primary slurry. The process is repeated three times. After it, secondary coating has been placed on the foam pattern. The thickness of coating (primary and secondary) has found 5-7 mm for all samples.

e)  

![Figure 1: Lost Foam Pattern](image)

All Dimensions are in mm
f) **Decomposition of coated expandable pattern:** Shell has been generated by removal of lost foam pattern by applying the heat in furnace. When 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 has been created. This process is called foam pattern removing. In this method, first, shell is preheated at 80°C for 30 minutes. After preheating, the temperature raises up to 120°C at a rate of 4°C/ minute. Shells are heated at constant temperature (120°C) for 20 minutes. Again 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. This process is repeated till foam evaporates completely.

2. **Result and Discussion:**

a) **Selection of Best Shell by using Analytical Hierarchy Process (AHP):**

There are many criteria (properties of shell) on which the shell quality depends, as following.

**Dimensional accuracy criteria:** Bending and Distending Resistance.

**Surface Finish criteria:** Internal and External Surface Finish of shell.

**Cost:** Cost of coating powder materials and Binder.

**Strength of Shell:** Crack Resistance.

For these alternatives and criteria, Saaty’s Hierarchy Tree has been shown in figure 2. In this investigation, the most important properties (bending and distending resistance, internal surface finish, crack resistance of shell) are considered. Following steps are used for finding the best alternative as per AHP.

**STEP 1: (Consideration)**

Select most important properties of shell (bending resistance as criteria A, distending resistance as criteria B, Internal surface finish as criteria C, and crack resistance as criteria D) and four shells (S1, S2, S3 and S4).
STEP 2: (Pair wise comparison)
In this step, the pair wise comparison of individual criteria with respect to all criteria has been taken place. Similarly, the pair wise comparison of individual alternative with respect to all alternatives for each criteria, has been analyzed.

Pair wise comparison of criteria:
- Criteria A is 3 times important than criteria B.
- Criteria B is 3 times important than criteria C.
- Criteria D is 1.5 times important than criteria C.
- Criteria A is 6 times important than criteria C.
- Criteria A is 5 times important than criteria D.
- Criteria B is 2 times important than criteria D.

Pair wise comparison of alternatives:
- For criteria A
  - Alternative S2 is 2 times important than alternative S1.
  - Alternative S3 is equal important than alternative S4.
  - Alternative S3 is 1.5 times important than alternative S1.
• Alternative S2 is 1.5 times important than alternative S3.

• For criteria B
  ➢ Alternative S1 is 1.5 times important than alternative S3.
  ➢ Alternative S2 is equal important than alternative S4.
  ➢ Alternative S3 is 1.5 times important than alternative S1.
  ➢ Alternative S2 is 2 times important than alternative S1.

For criteria C
  ➢ Alternative S2 is equal important than alternative S3, S4.
  ➢ Alternative S2 is 2 times important than alternative S1.

• For criteria D
  ➢ Alternative S2 is equal important than alternative S1.
  ➢ Alternative S3 is equal important than alternative S4.
  ➢ Alternatives S2 and S1 is 2 times important than alternative S3 and S4.

STEP 3: (Generation of matrix as per pair wise comparision)
In this step, the matrix form has been generated as per pairwise comparision.

• For all criteria:

|    | A    | B    | C    | D    |
|----|------|------|------|------|
| A  | 1.000| 3.000| 6.000| 5.000|
| B  | 0.333| 1.000| 3.000| 2.000|
| C  | 0.167| 0.333| 1.000| 0.667|
| D  | 0.200| 0.500| 1.500| 1.000|

• For all alternatives:

For Criteria A:

| S1 | S2 | S3 | S4 |
|----|----|----|----|
| 1.000 | 0.500 | 0.667 | 0.667 |

For Criteria B:

| S1 | S2 | S3 | S4 |
|----|----|----|----|
| 1.000 | 0.500 | 0.667 | 0.500 |

| S1 | S2 | S3 | S4 |
|----|----|----|----|
| 2.000 | 1.000 | 1.500 | 1.500 |

| S1 | S2 | S3 | S4 |
|----|----|----|----|
| 1.500 | 0.667 | 1.000 | 1.000 |

| S1 | S2 | S3 | S4 |
|----|----|----|----|
| 2.000 | 1.000 | 1.500 | 1.000 |
For Criteria C:

|   | S1    | S2    | S3    | S4    |
|---|------|------|------|------|
| S1| 1.000| 0.500| 0.500| 0.500|
| S2| 2.000| 1.000| 1.000| 1.000|
| S3| 2.000| 1.000| 1.000| 1.000|
| S4| 2.000| 1.000| 1.000| 1.000|

For Criteria D:

|   | S1    | S2    | S3    | S4    |
|---|------|------|------|------|
| S1| 1.000| 1.000| 0.500| 0.500|
| S2| 1.000| 1.000| 0.500| 0.500|
| S3| 2.000| 2.000| 1.000| 1.000|
| S4| 2.000| 2.000| 1.000| 1.000|

**STEP 4: (Finding the eigen vector for each matrix)**

In this step, the eigen vectors are calculated by squaring the matrix and then adding each row as describe below.

|   | A  | B  | C  | D  |
|---|----|----|----|----|
| A | 1.000| 3.000| 6.000| 5.000 |
| B | 0.333| 1.000| 3.000| 2.000 |
| C | 0.167| 0.333| 1.000| 0.667 |
| D | 0.200| 0.500| 1.500| 1.000 |

**Squaring the matrix**

\[
\begin{bmatrix}
1.000 & 3.000 & 6.000 & 5.000 \\
0.333 & 1.000 & 3.000 & 2.000 \\
0.167 & 0.333 & 1.000 & 0.667 \\
0.200 & 0.500 & 1.500 & 1.000 \\
\end{bmatrix} \times \begin{bmatrix}
1.000 & 3.000 & 6.000 & 5.000 \\
0.333 & 1.000 & 3.000 & 2.000 \\
0.167 & 0.333 & 1.000 & 0.667 \\
0.200 & 0.500 & 1.500 & 1.000 \\
\end{bmatrix}
\]
SQ is square matrix

\[
\begin{bmatrix}
4.000 & 10.498 & 28.500 & 20.002 \\
1.567 & 4.000 & 10.998 & 7.666 \\
0.578 & 1.501 & 4.000 & 2.835 \\
0.817 & 2.100 & 5.700 & 4.000
\end{bmatrix}
\]

Eigen Vector

\[
\begin{align*}
\text{Total of each row} & = 63.001 \\
\text{Total of each row} & = 24.229 \\
\text{Total of each row} & = 8.915 \\
\text{Total of each row} & = 12.517
\end{align*}
\]

Total = 108.762

| Criteria | Value |
|----------|-------|
| A        | 0.579 |
| B        | 0.223 |
| C        | 0.082 |
| D        | 0.116 |

Again finding eigen vectors of the square matrix we get the following matrix

\[
\begin{align*}
\text{A} & \quad 0.579 \\
\text{B} & \quad 0.223 \\
\text{C} & \quad 0.082 \\
\text{D} & \quad 0.116
\end{align*}
\]

Most important criteria

Second most important criteria

Least most important criteria

Third most important criteria

Similarly

For criteria A

\[
\begin{align*}
0.166 & \quad \text{Least important alternative} \\
0.352 & \quad \text{Most important alternative} \\
0.241 & \quad \text{Second most important alternative} \\
0.241 & \quad \text{Second most important alternative}
\end{align*}
\]

For criteria B

\[
\begin{align*}
0.153 & \quad \text{Least important alternative} \\
0.315 & \quad \text{Most important alternative} \\
0.217 & \quad \text{Second most important} \\
0.315 & \quad \text{Most important alternative}
\end{align*}
\]
For criteria C

0.142 → Least important alternative
0.286 → Most important alternative
0.286 → Most important alternative
0.286 → Most important alternative

For criteria D

0.167 → Least important alternative
0.167 → Least important alternative
0.333 → Most important alternative
0.333 → Most important alternative

STEP 5: (Finding the best alternative)

In this step, the best alternative is found by multiplying the criteria alternative matrix and criteria rank.

| A   | B   | C   | D   | Criteria Rank |
|-----|-----|-----|-----|---------------|
| S1  | 0.166 | 0.153 | 0.142 | 0.167 | 0.578 | 0.161 |
| S2  | 0.352 | 0.315 | 0.286 | 0.167 | 0.223 | 0.317 | BEST |
| S3  | 0.241 | 0.217 | 0.286 | 0.333 | 0.082 | 0.250 |
| S4  | 0.241 | 0.315 | 0.286 | 0.333 | 0.116 | 0.272 |

The result of AHP shows that alternate sample no. 2 is selected as the best shell. This is because the important factors are considered as priority.
Conclusions:

By incorporating the all-important properties like bending resistance, distending of shell, internal surface finish and crack resistance, sample no. 2 has found as the most optimized. So, optimum composition of coating material (sample no. 2) is aluminium silicate 30%, zircon 20% with binder sodium silicate 50 % for primary coating.

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