Effect of Process Parameters on Hardness of AA-6063 In-Situ Microwave Casting by Using Taguchi Method

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Abstract. In-situ microwave casting is one of the recently developed advanced metal casting techniques in which the bulk metal and mould assembly are exposed to microwave radiations at 2.45 GHz. In in-situ microwave casting, the exposure and self-pouring is done inside the microwave. The cast quality that has been casted through the microwave casting process is directly dependent on the process parameters that are selected during the process. This paper explores the effect of process parameters on hardness of AA-6063 by using microwave hybrid heating technique. Apply Taguchi L9 orthogonal array to conduct the experimentations. Here consider three process parameters: solidification environment, susceptor material and microwave power.

Keywords: Microwave hybrid heating, AA6063, Susceptor, SiC, L9 orthogonal Array.

1. Introduction

The process of casting layouts are very effective path through which achieve the final shape to convert liquid metal in solid form [1]. Casting is very pliable process to manufacture the different size and shape. It also provides pliability to produce number of castings [2]. The melting and rate of metal solidification during casting affects metallurgical and mechanical properties of the final product [1, 2]. Solidification of the alloys take place over a temperature range and it consists of both solid and liquid phases. During the starting of solidification, the solid phase nucleates and dendritic structure forms. Thus, during the alloy casting set the benchmark of solidification that improves thermo-mechanical properties in the alloy cast [3]. AA-6063 possesses good mechanical properties such as tensile strength and hardness at atmospheric temperature. This AA-6063 is widely used in the applications of architectural fabrication, marine applications and aerospace applications [4].However, the improper solidification rates causes many casting defects named as cold shut, hot tears and misrun because of high cooling rate [3].

Processing through microwave energy produce sounded parts that have higher-ranking material properties and causes better microstructure approach. Microwave processing of materials is less time consuming and neat and clean process. It also very cost efficient and rate of power consumption is very less as compared to other material processing methods [5]. Through the microwave applicator powdered form of metal is also processed easily without any material and heat loss [6]. Exposure of metal in the microwave applicator is very risky because the microwave radiations reflected back while impinge on metal surface which leads destruction in microwave applicator. Still through the principle
of microwave hybrid heating, metals can be processed. For this purpose use susceptor materials which absorb the microwave energy that increase the temperature of metal that is processed.

Processing of metal-based materials is a recently developed material processing technique by utilizing microwave energy of the frequency at 2.45 GHz [7, 8]. Low energy requirement, low energy consumption, high safety and negligible pollution in atmosphere through MHH technique which leads in conventional casting methods [8, 9]. In the year 2005, first literature report about the bulk melting of iron, tin, cupper and aluminium through microwave processing into the applicator [10]. Also pouring of bulk metal in pouring basin, melting and flow to the cavity through the sprue and cooling was done inside the applicator [11]. Chandrasekaran et al also illustrate the characteristics of melting process of different material such as lead, aluminium and copper through the microwave energy [12].

Recently, lead [13], copper [8] and aluminum alloy [14-15] were casted in-situ inside applicator cavity using a multi-mode microwave applicator 2.45 GHz. Microwave heating of the metallic materials due to the microwave casting process depends upon efficient conversion of electromagnetic energy of microwave radiations into heat energy. This conversion of energy through which bulk metal melts fully dependent on the mechanical properties and heating characteristics of mold setup [15].

Numerous techniques of optimization are available which provide the interactions between input parameters and their output response. Through these optimization techniques maintained the soundness of the desired casting. Some researchers proposed the Taguchi philosophy for the Vacuum casting through which optimized the various properties of casting. Also explained the influence of process variables on the process and their measured properties [16]. Some analyzed that in die casting, significant variations in process variables to achieve the better yield in density of casting in the casting of AA [17]. Some researchers proposed the concept of robust design so that minimize the cost and better yield in quality of Al alloy [18].

In the casting of gear blank, process variables are optimized through the robust design methods. They possessed that various casting parameters also influence the characteristics of cast. Weight of casting compared to desired weight also taken in consideration which leads the casting defects [19]. Shajie et al [20] described the surface grinding process in which use graphite as a lubricant through the Taguchi philosophy. In this research paper three process parameters were selected as speed, feed and method of dressing. Apply the Taguchi philosophy and analyzed that these parameters greatly affect the output response in term of surface finish and the event of forces. Some apply the Taguchi optimization technique to optimize the process parameters in end milling process in which the milling of steel with carbide tool with coating of tin for the end operations at very high cutting speed [21]. George and Raghunath [22] experimented on EDM process for machining of carbon composites use the Taguchi philosophy.

All the literature review showed that the optimization of process parameters in casting process, Taguchi philosophy is the best suitable optimization technique. However, no past literature was reported about the process parameter optimization through Taguchi method in microwave casting process. In this work, selected process parameters named susceptor, solidification environment and microwave power are optimized through Taguchi design method. Effect of process parameters on the mechanical properties of AA-6063 through microwave casting process at three microwave power range 900W, 750W and 600W was investigated. Casting developed at these three levels was investigated to measure Hardness as a output response characteristics.

2. Experimentation
In this work, casting were developed through the microwave energy using microwave power in the range of 900W, 750W and 600W with domestic microwave applicator at 2.45 GHz (SAMSUNG Model-MC35J8085PT, Black). All work had done at room conditions where no use of external shielding gas. Solidification has to be done on three different solidification medium (closed cavity, open cavity and air cooled).
2.1 Material Details
In this work aluminium alloy AA-6063 is selected as the charge material. This alloy possesses good mechanical properties during casting process. Chemical compositions and mechanical properties of AA-6063 are shown in table 1 and table 2.

Table 1. Elemental composition of as received AA6063 alloy

| Elements | Si  | Fe  | Cu  | Mn  | Mg  | Ti  | Al   |
|----------|-----|-----|-----|-----|-----|-----|------|
| % wt     | 0.48| 0.20| 0.02| 0.03| 0.52| 0.01| bal  |

Table 2. Mechanical properties of AA-6063 alloy

| Young’s Modulus | Tensile Strength | % Elongation | Poisson’s Ratio |
|-----------------|------------------|--------------|----------------|
| 68.4 GPa        | 145-186 MPa      | 18-34%       | 0.3            |

To maintain the temperature of the material that is melted use the susceptor material which absorb the microwave radiations which impose on it and they transfer the total radiated heat to the material that is processed and achieve the melting temperature. Susceptor materials transfer the heat through the convection method of heat transfer. In this research three susceptor materials are utilized i.e. silicon carbide, stone charcoal and wood charcoal.

2.2 Process Parameters
The process parameters are the initial inputs to the experimental process which definitely affect the final outcomes. Any experimentation is directly based on many process parameters in which some parameters are fixed and some are variable. All these parameters are illustrated by the Ishikawa diagram in figure 1.

Perform various experiments to establish the range of the process variables. Apply Taguchi L9 orthogonal array to perform the experiments by adopting the factors named susceptor material, solidification environment and microwave power output with three levels each. Response selected was hardness of casts produced at microwave power range of 900W, 750W and 600 W.

Figure 1. Ishikawa cause and effect diagram
Table 3. Process parameters and their levels

| Levels | Susceptor materials          | Solidification Environment | Microwave power (W) |
|--------|-----------------------------|----------------------------|---------------------|
| 1      | SiC                         | Closed Cavity              | 900 W               |
| 2      | Stone Charcoal              | Open Cavity                | 750 W               |
| 3      | Wood Charcoal               | Air Cooled                 | 600 W               |

2.3 Principle of microwave casting

Casting through the microwave energy is due to the application of susceptor. Susceptor causes to attain the localized heating to the predefined area where the bulk charge is placed and being processed. Setup of microwave casting used the alumina to maintain the heat inside the cavity and decreased the loss of heat. Acetone is used to wipe the cast prior to casting of total mass of metal. The complete assembly of mold was placed into the applicator cavity to produce the castings of aluminum. That cavity is modified according to the need. The cavity was associated with air passage so that cavity became cooled and temperature of applicator body should be maintained. To measure the temperature of charge material installed the built-in-pyrometer whose range from 300 °C to 1800 °C. Experimentations had been done on aluminum alloy. Charge material was processed in microwave hybrid heating and poured inside the pouring basin made up of graphite crucible which has a good microwave absorption characteristic. Mold and sprue was made up of graphite also. Mold is split in cope and drag so that molten alloy should be casted inside the cavity. So different susceptor was used for better heat transfer rate during microwave radiations on charge materials such as SiC, wood charcoal and stone charcoal. The complete mold assembly in the applicator was covered with refractory insulation material to minimize the heat loss. The mold cavity was processed at 3 microwave power ranges of 900W, 750W and 600W. The final castings were solidify in three different environments are closed cavity, open cavity and air cooled.

2.4 Selection of an orthogonal array (OA)

There are various approaches to select the particular orthogonal array to conduct the experiments. To do so there are some points that should be in mind [23, 24] :
- The number process parameters and their interactions of requirement.
- The number of process parameters levels of requirement.
Consider the 3 levels and their 3 factors so utilized L9 orthogonal array for the experimentations. Each factor have DOF is 2 (No. of levels -1, -1=2) so the total DOF for the experimentations will be 3*2=6
Usefulness of the S/n ratio is to improve the quality through variability reduction. The S/N ratio characteristics can be divided into three categories.
(a) Nominal is the best
\[ S/N = -10 \times \log (\sigma^2) \]
(b) Smaller is the better
\[ S/N = -10 \times \log (\Sigma (Y^2/n)) \]
(c) Larger is the better
\[ S/N = -10 \times \log [\frac{1}{n} \Sigma (\frac{1}{y^2})] \]

2.5 Experimental Procedure

The preheated AA 6063 pieces with dimension 10mm×10mm×4mm is placed in the cavity that is made up of graphite. Then the cavity was totally covered with graphite sheet so that the surrounding contaminants not deposited in the cavity. Charge materials are filled to the mold cavity and mold cavity was covered with susceptor. Susceptor are used so that it coupled with microwaves and heating
of charge takes place through conventional methods. All experiments were performed in the domestic microwave applicator and the microwave casting process is shown in fig. 2. Mold setup was placed over the alumina bricks that were highly refractive so that total heat produced inside the cavity should be maintained throughout the cavity and there was no heat loss to the rotary glass table. The solution of equal amount of HNO$_3$+HCL+CH$_3$COOH was prepared for etching. Then the samples were washed and dried through the atmospheric air.

**Table 4.** Taguchi Design Matrix

| Sr. No. | Column 1 | Column 2 | Column 3 | Microwave Power (W) | Susceptor Material | Solidification Environment |
|---------|----------|----------|----------|---------------------|--------------------|---------------------------|
| 1       | 1        | 1        | 1        | 600                 | WC                 | Closed Cavity             |
| 2       | 1        | 2        | 2        | 600                 | SC                 | Open Cavity               |
| 3       | 1        | 3        | 3        | 600                 | SiC                | Air Cooled                |
| 4       | 2        | 1        | 2        | 750                 | WC                 | Open Cavity               |
| 5       | 2        | 2        | 3        | 750                 | SC                 | Air Cooled                |
| 6       | 2        | 3        | 1        | 750                 | SiC                | Closed Cavity             |
| 7       | 3        | 1        | 3        | 900                 | WC                 | Air Cooled                |
| 8       | 3        | 2        | 1        | 900                 | SC                 | Closed Cavity             |
| 9       | 3        | 3        | 2        | 900                 | SiC                | Open Cavity               |

**Figure 2.** Schematic representation of microwave hybrid heating process for casting of AA 6063
3. Result and discussions

3.1. Hardness Test

According to L9 OA, nine experiments have been performed and measured the hardness which is shown in table 4. Signal to noise (S/N) ratio of hardness for every process variable at all levels and raw data mean response are generated by Minitab 18 are shown in table. The results of S/N ratio were also calculated through Taguchi method shown in table 5. The response graph of S/N ratio is shown in figure 5. This analysis showed that factors at the levels power3, susceptor3 and cooling environment3 are the best levels that give the maximum value of hardness.

After indentation, the specimens are shown in fig. 4 as below.
Table 5. Test data summery for Hardness

| Experimental Run | Power A | Susceptor B | Solidification environment C | Hardness | S/N ratio (db) |
|------------------|---------|-------------|-------------------------------|----------|---------------|
| 1                | 600     | WC          | INCAVITY                      | 37       | 31.3640       |
| 2                | 600     | SC          | OUT CAVITY                    | 38       | 31.5957       |
| 3                | 600     | SIC         | AIR COOLING                   | 44       | 32.8691       |
| 4                | 750     | WC          | OUT CAVITY                    | 43       | 32.6694       |
| 5                | 750     | SC          | AIR COOLING                   | 40       | 32.0412       |
| 6                | 750     | SIC         | IN CAVITY                     | 42       | 32.4650       |
| 7                | 900     | WC          | AIR COOLING                   | 45       | 33.0643       |
| 8                | 900     | SC          | IN CAVITY                     | 29       | 31.8213       |
| 9                | 900     | SIC         | OUT CAVITY                    | 47       | 33.4420       |

Average 32.3702

Table 6. Response Table for Signal to Noise Ratios

| Levels | Power A | Susceptors B | Solidification environment C |
|--------|---------|--------------|------------------------------|
| 1      | 31.94   | 32.37        | 31.88                        |
| 2      | 32.39   | 31.82        | 32.57                        |
| 3      | 32.78   | 32.93        | 32.66                        |
| Delta  | 0.83    | 1.11         | 0.77                         |
| Rank   | 2       | 1            | 3                            |

Figure 5. Response graph of S/N Ratio
Maximum hardness (47) is obtained at highest microwave power 900W, susceptor SiC and air cooled cooling environment of casting, cleared from table 4.

It is clear from figure 5 and table 4 that as the microwave power increases the hardness increases. This is because at higher microwave power the temperature increases due to heat generated is higher. Higher temperature causes grains of the cast alloy will be reformed due to which recrystallization takes place throughout the cast which increase the bonding between the grain particles causes increase hardness.

Figure 5 and table 4 revealed that as susceptor material also affect the hardness of the cast in MW casting process. SiC susceptor have the highest absorption rate to absorb the microwave radiations causes increase the hardness.

It can be visualized from figure 5 and table 4 that as the cooling environment also influence the hardness. If solidification takes in the short period of time then the hardness increase. Here cooling takes place in atmospheric air cause rapid formation of grain boundaries causes increase the hardness.

By analyze the validation of process variables for hardness, performed ANOVA (analysis of variance). ANOVA is performed in table 11 in which degree of freedom (DF), variance (MS), variance ratio (F), sum of square (SS) and significant factor (P) are illustrated. The significant value of factor was selected always less than 5% (p ≤ 5).

Table 7. ANOVA for Hardness (S/N ratio)

| Source          | Degree of Freedom | Adj SS   | Adj MS   | F-Value | p-Value |
|-----------------|-------------------|----------|----------|---------|---------|
| Power           | 2                 | 24.0000  | 12.0000  | 36.00   | 0.027   |
| Susceptor       | 2                 | 42.6667  | 21.3333  | 64.00   | 0.015   |
| Solidification  | 2                 | 24.6667  | 12.3333  | 37.00   | 0.026   |
| Error           | 2                 | 0.6667   | 0.3333   |         |         |
| Total           | 8                 | 92.0000  |          |         |         |

3.1.1 Estimation of output characteristics

The average value is being refers by mean response. The average values of hardness were calculated and given in table 8.

Table 8. Main effect on Harness (raw data)

| Process Parameters | Level | Microwave Power (A) | Susceptor (B) | Solidification Environment (C) |
|--------------------|-------|---------------------|---------------|-------------------------------|
| Average Values     | L₁    | 39.66               | 41.67         | 36                            |
|                    | L₂    | 41.67               | 35.67         | 42.67                         |
|                    | L₃    | 40.33               | 44.33         | 43                            |
| Main Effect (hardness) | L₂ - L₁ | 2.01              | -6            | 6.67                          |
|                    | L₃ - L₂ | -1.34             | 8.66          | 0.33                          |
| Difference         | (L₃ - L₂) - (L₂ - L₁) | -3.35       | 20.66         | -6.34                         |

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.
The optimal hardness value is forecasted based on level of optimum process parameters. The optimum process variables and their level of optimization being prior opted as (3-3-3); 3 = at level 3, the optimum value of hardness is obtained at microwave power of 900W and susceptor of SiC respectively, 2 = at level 2, the optimum value of hardness is obtained at air cooling environment. The mean of characteristic of response can be calculated as

$$\mu_{\text{hardness}} = H_{A3} + H_{B3} + H_{C3} - 2H_{\text{avg}}$$

Where,

- $H_{\text{avg}} = $ Overall mean hardness = 40.55
- $H_{A3} = $ Value of average hardness for microwave power at level 3 factor= 40.33
- $H_{B3} = $ Value of average hardness for susceptor at level 3 factor = 44.33
- $H_{C3} = $ Value of average hardness for solidification environment at level 3 factor = 43

Hence,

$$\mu_{\text{hardness}} = 40.33 + 44.33 + 43 - 2 \times 40.55 = 46.56$$

The 95% confidence intervals of confirmation experiments (CI$_{CE}$) can be calculated by using the equation as mentioned below.

$$CI_{CE} = \sqrt{F_0(1, f_e)V_e\left[\frac{1}{\eta} + \frac{1}{r}\right]}$$

Where, error variance = $V_e$, F ratio ($F_\alpha(1, f_e)$) for the level of confidence i.e, (1-$a$) for degree of freedom 1 and $f_e$ is error of DOF. Confidence level is “$a$”.

Effective number of replications ($\eta$) is calculated using equation,

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

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:

$$(\mu_{\text{hardness}} - CI_{CE}) < \text{Hardness} < (\mu_{\text{hardness}} + CI_{CE})$$

44.52 < Hardness < 48.60

4. Confirmation Test

Three confirmation experiments were conducted at the optimum setting of the process parameters.

4.1 Hardness

From the above results shown in table no. 4, it is observed that optimum parameters are 900 W microwave powers, SiC as a susceptor and air cooled cooling environment. L9 orthogonal array does not show the optimum combination so confirmation test is performed. For the confirmation test, it is required to conduct some experiments based on given table no. 9.

| S.No. | Combination of optimum experimental parameters | Hardness | Avg. Hardness |
|-------|-----------------------------------------------|----------|--------------|
| A     | B     | C        |            |
| 1     | 900 W | SiC      | Air Cooling| 48           |
| 2     | 900 W | SiC      | Air Cooling| 47.7         |
| 3     | 900 W | SiC      | Air Cooling| 48.8         |
It is observed that the value of hardness is 47 BHN at out cavity cooling environment. When cooling environment is changed to air cooling, the value of hardness increase to 48.17 BHN (Avg.) as shown in table no. 9 as other two parameters are same. So the optimum parameter of cooling environment changed from out cavity to air cooling.

5. Microstructure Study
In this research paper microstructure study was done to compare the microwave assisted casting to the evaporated pattern casting and conventional sand casting methods.

Figure 6. Comparison of Microstructures of (a) Conventional sand casting process, (b) Evaporated pattern casting method and (c) Microwave hybrid heating casting

Microstructure shows that porosity was maximum in conventional sand casting and evaporated pattern casting [25]. Porosity was observed in microwave casting process was very less as compared to others. So microwave casting process provides better results than other casting methods.

6. Conclusions
After conducting the experimentations, reached to the conclusion on the basis of process parameters.
1. Susceptor material and microwave power significantly affect the hardness.
2. The optimal levels of microwave power, susceptor material and solidification environment were estimated for best hardness results.
3. The predicted optimal range for hardness is: 44.52 < Hardness < 48.60.

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