Identification, screening and optimization of significant parameters for stir cast hybrid aluminium metal matrix composite

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Abstract

Different industries have explicit applications of Aluminum Metal Matrix Composites (AMMCs). However, porosity, wettability and Ultimate Tensile Strength (UTS) are important factors that need to consider while fabricating AMMCs. This paper focuses on identification of the most significant parameters for low porosity and high ultimate tensile strength (UTS) of hybrid aluminium metal matrix composite. Significant as well as non-significant factors were identified from the literature survey and trial experiments. Without considering the significance of given responses, identified factors were represented graphically by the fishbone diagram. FMEA (Failure Mode and Effect Analysis) was used to find out significant parameters from all the parameters that represented by fishbone diagram. Afterwards, Plackett-Burman design was used to screen the most significant parameters out of the significant parameters. Stirring speed, stirring time, preheating temperature and reinforcement amount was found the most significant parameters to attain high UTS and low porosity. However, because of the unfavourable combination of parameters % porosity increased beyond 7% during screening design based experiments. Subsequently,
these parameters were optimized by factorial design. The result shows optimized
parameters stirring speed 650 rpm and stirring time 12 minutes provides low
porosity and high UTS. UTS improved up to 310 MPa due to an optimized
range of stirring speeds and stirring time. However, porosity increased beyond
3% due to excess stirring in cast composites during factorial design based
experiments. Moreover, studies were carried out to understand the effect of
stirring, fluxing, degassing and moulding methods on porosity, UTS, clustering
and surface finish of the cast composite. It was observed from a supplementary
study that permanent mould reduces surface roughness below 3μm, compared to
the sand casting process. The porosity was reduced below 3% by degassing and
fluxing. Low agglomeration was observed in specimen prepared with automatic
stirring process compared to the manually stirred specimen. Compared to others,
in specimen 4, UTS was improved beyond 150 MPa because of permanent
mould, automatic stirring, degassing and fluxing.

Keywords: Metallurgical engineering, Materials science, Mechanical engineering

1. Introduction

As pointed out by Suthar and Patel (2017), there are various applications of the
AMMCs in industries from aerospace to consumer utility industries that suggest de-
mand of novel material for specific applications in industries. Moreover, Prasad and
Asthana (2004) listed out the specific applications of aluminum metal matrix com-
posite in automobile industries. Al/SiC composite in automobile industries are used
for the fabrication of the pistons, connecting roads, propeller shafts, brake rotors etc.
while Al/Al2O3 composites are used for engine blocks, piston rings and connecting
roads. However, as indicated by Gay (2014) that composite materials are being used
since ancient times for the production of conventional weapons and artefacts (i.e.
Mongolian bows, Damask sword, Merovingian blades, Egyptian dagger ornamented
with gold powder, Iron pillar of Delhi, Japanese sabers etc.). Moreover, as
mentioned by Aleksendric and Carlone (2015) that composite material like
polymer-cellulose fibres was found in wood. Therefore, the idea of the composite
is not a human invention at all. In composite fabrication processes reinforcement ma-
terials of different forms (i.e. fibres or particles) are inserted in a weaker material (i.e.
matrix material) for the fabrication of composite materials. This provides intermed-
iate properties to a composite material compared to a matrix and the reinforcement
materials. Hull and Clyne (1996) stated that there are mainly 3 types of matrix ma-
terials available i.e. polymer matrix, mineral matrix, and metal matrix while, partic-
ulate, discontinuous fibre and continuous fibre are the different form of the
reinforcement materials available for composite development.
Ezatpour et al. (2014) conducted an empirical study to investigate the mechanical performance of nanocomposite fabricated using stir casting method, which shows that porosity wettability, particle distribution, and chemical reaction are the major problems that hinder industrial acceptability of metal matrix composites. Staiger et al. (2006) conducted a review to find out the possibility of magnesium and its alloys as orthopaedic biomaterials and they concluded that mechanical properties, surface integrity and corrosion behaviour of the materials largely depend on porosity size, quantity, and distribution within the material. Hu et al. (2016) observed a similar result during fabrication of Al-B₄C composite using stir casting. They found that porosity gives rise to an uneven distribution of reinforcement, reduce hardness and yield strength. Moses et al. (2016) mentioned that insufficient pressure due to higher stirring speed produces porosity in stir cast metal matrix composite. Likewise, Dahle et al. (2001) conducted an empirical study to examine the microstructure of as-cast magnesium-aluminium alloy and concluded that dissolved hydrogen produces micro-porosity. Prabu et al. (2006) observed similar results during fabrication of metal matrix composite. They have fabricated stir cast composites to find out the influence of stirring speed and stirring time on particle distribution and concluded that incomplete evacuation of gases (i.e. hydrogen) produces porosity. However, it is very difficult to avoid porosity in the casting process and therefore, Suthar and Patel (2017) recommended minimization of porosity.

Sabbaghiandrad and Langdon (2016) fabricated aluminium metal matrix composite using high-pressure torsion technique and measured the mechanical properties of the composite. They noted that mechanical properties are important to predict the behaviour of the material. Along the same line, Ibrahim et al. (2015) conducted an experimental study to find out the effect of B₄C addition in pure aluminium and its alloys. They observed improvement in flexure strength, ultimate tensile strength and compression strength of the composite with an increase in B₄C amount. Contrary results were observed by Muthazhagan et al. (2014) during fabrication of Al/graphite composite. Researchers found that ductility, hardness, and ultimate tensile strength reduce with increase in graphite amount. However, Baradeswaran and Perumal (2014) produced Al 7075/graphite composite and spotted that graphite reduces the wear rate and the friction coefficient drastically. Therefore, the use of graphite is essential to improve the wear resistance properties.

Marmur et al. (2017) specifically defined the wettability as the level of close contact between liquid metal (i.e. matrix metal) and solid reinforcement particles. Wang et al. (2015) synthesized TiC/Al nano size composite by an in-situ method. Researchers analyzed the composite for microstructure and tensile properties and recommended high wettability for a strong bond between reinforcement and matrix material. Whereas, low wettability depreciates mechanical, wear resistance and corrosion resistance properties of AMMCs. Moreover, Omrani et al. (2016) conducted a review to reveal the influence of graphite particles on the tribological behaviour.
of Al/graphite composite and established that wetting agents such as Mg, Ti, Ca, Zr, Sc etc improves wettability by forming a provisional layer between matrix and reinforcement. A low wetting angle of provisional layer reduces surface tension that improves wettability and therefore it is essential to add wetting agents to improve wettability between the aluminium matrix and graphite reinforcement.

Hashim et al. (1999) acknowledged different methods to fabricate Metal Matrix Composites (MMCs) such as vapour deposition, liquid-state, solid-state, semi-solid state, and in-situ fabrication technique. Similarly, Bains et al. (2016) conducted a review to present a progress and benefits of different methods of fabrication of composites. They accepted that except liquid state method, all require expensive set-ups and are difficult to absorb in general industrial purpose. Therefore, from mass production and economic perspective, the liquid state method is convenient and reliable.

Guiffrida and Messina (2015) used a fishbone diagram as one of the technique to represent and resolve the problems of controlling service quality. They found it a very useful analytical tool that provides a systematic way of looking at effects and the causes that affect response. Therefore, in the present study, without considering the significance of the factors, authors have used the fishbone diagram to represent factors that affect a particular response. Schmittner et al. (2014) used FMEA in their study to identify significant parameters that affect the security of the software and concluded that FMEA is one of the suitable methods to derive the significant parameters. Hence, in the present study, authors have used this method to segregate significant parameters from the parameters represented by the fishbone diagram. Furthermore, Sha et al. (2017) demonstrated a method to extract the phytic acid from defatted rice bran and for that researchers used Plackett-Burman design to screen out the most significant factors. They concluded that Plackett-Burman design saves time when study consists of multiple variables. Correspondingly, Vanaja and Shobha Rani (2007) and Guzun et al. (2014) reviewed the applications of Plackett-Burman design in the field of formulation development and composite synthesis respectively. They mentioned explicitly that Plackett-Burman design reduces the number of factors and thereby saves time and money in more elaborate experiments. Similar, therefore, in the current study, authors have used Plackett-Burman design for segregation of the most significant factors.

Therefore, authors, from this current study want to explain the sequence of methods to find out the most significant parameters for the given responses of the composite material. This would help the researchers to make the composite research more economical at the laboratory and industrial scale. Therefore, following methods are discussed in the current paper; (a) the way to find out the parameters that affect the responses irrespective to their significance for the responses; (b) the method of representation for these factors; (c) the method of screening to find out the significant
parameters out of these factors; (d) method of further scanning to find out the most significant parameter to make the research economical and; (e) the method of optimization to optimize the most critical parameters.

2. Materials & methods

2.1. FMEA and fishbone diagram

Suthar and Patel (2017) showed various factors based on the literature that affect porosity, wettability, particle distribution and other properties of AMMCs. Data to represent fishbone diagrams were taken from the review conducted by Suthar and Patel (2017). Hence, Figs. 1 and 2 show fishbone diagrams to represent the factors that affect UTS and porosity respectively. Parameters related to human capabilities, environmental condition, machining process, matrix materials, reinforcement materials, etc. were considered during the representation. Factors for FMEA were selected from the fishbone diagram. In FMEA, risk priority number (RPN) for each factor was calculated from occurrence, severity and detection score as shown in Eq. (1). The occurrence score shows the frequency of achieving response with change in the parameter. Severity score shows a seriousness of parameter variation that affects responses while the detection score shows the ability to detect the response with parameter variation. In each category, five and one were considered the highest and lowest score respectively. The score in each category for a particular factor was given based on the literature and experience. Threshold was set at 60% (i.e. RPN = 75) of highest RPN value (i.e. RPN = 125). Figs. 3 and 4 represent FMEA of UTS and porosity respectively.

Fig. 1. Fish-bone diagram for Ultimate Tensile Stress (UTS) (Suthar and Patel, 2017)
2.2. Experimental setup and materials

As shown in the Fig. 5, mini electric furnace and stirrer were used to develop the basic stir casting facility. Furnace consists of an inbuilt temperature sensor and digital temperature indicator while stirrer consists of a regulator and digital indicator for speed control. Stirring time was measured using a stopwatch. Pure graphite moulds were prepared to cast the round bars. Aluminium (98% pure) as ingot, while B₄C (99% pure), Ti (99% pure) and graphite (99% pure) were used in powder form. However, Mg was used in thin plate and ribbon form as a precaution. Optical Emission Spectrometer (OES) was used to get the quantitative estimation of pure aluminium. Table 1 shows the chemical composition of the aluminium ingot.

\[ \text{RPN} = \text{Occurrence} \times \text{Severity} \times \text{Detection} \]  

(1)
2.3. Screening design

Plackett Burman design was used to segregate most significant factors out of significant factors derived from FMEA. However, the feasibility of stir casting process and availability of the resources were considered during the selection of the factors for

![Fig. 4. FMEA graph for Porosity.](image)

![Fig. 5. Experimental setup for stir casting.](image)

**Table 1.** Chemical Composition of aluminium metal matrix (values show % of each element).

|   | Al  | Si  | Fe  | Cu  | Mn  | Mg  | Zn  | Ti  | Cr  | Ni  | Pb  | Sn  |
|---|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
|   | 98.800 | 0.510 | 0.500 | 0.012 | 0.042 | 0.027 | 0.023 | 0.008 | 0.006 | 0.008 | 0.046 | 0.002 |

![Table 1](image)
screening design. Statistical software Minitab®17.0.1 was used for the data analysis. Stirring speed, stirring time, stirring position, holding time, holding temperature, reinforcement particle size, reinforcement percentage, preheating temperature and mould temperature are the independent variables (i.e. obtain from FMEA) for the screening design while porosity and UTS are the responses. Furthermore, levels for each factor were selected based on literature availability. Composites were prepared using the levels suggested in Table 2. During the fabrication stage, amount of B₄C was varied from 5 to 20 wt%, whereas other reinforcements were maintained constant. Table 3 shows the methodology adopted during the fabrication of composite.

2.4. Optimization design

Ji et al. (2016) performed a study to formulate the curcumin solid lipid nanoparticles with other excipients, to enhance the solubility and bioavailability of curcumin. Researchers used screening design to find out the individual significant parameter and the combined effect of significant parameters on the fabrication process. They concluded that screening design does not show the interaction effect, which is the drawback of this design. Therefore, it is difficult to figure out the combination of parameters responsible for the change of response. Moreover, it does not suggest the level of the parameters. Therefore, as mentioned by Yoon (2007) in his study that the optimization of parameters is necessary after screening. Therefore, 2² factorial design was used to optimize the screened parameters for high UTS and low porosity. To reduce the complexity of work and to make research economical, preheating temperature and percentage reinforcement were kept constant during the optimization process. Table 4 shows the design matrix of the factorial design; it is evident from the table that stirring speed and time are the independent parameters while porosity and UTS are dependent parameters. Levels for stirring speed and stirring time were kept 600—1000 rpm and 10—60 minute respectively. It is important to note that during experiments, percentage reinforcement was kept constant (i.e. B₄C 10%, Mg 3%, Ti 0.2% and Graphite 5%) to find out the effect of stirring speed and stirring time.

Initially, % wt of reinforcement powders was converted into an actual weight using Eq. (2). Then weight was measured using a precision weighing machine (Sartorius CP124S). As observed by Boostani et al. (2015), milling generates uniform mixing of reinforcement material and hence, improves chances of uniform distribution of reinforcements in the melt. Therefore, measured quantities of powders (i.e. except Mg) were mixed uniformly for 20 minutes using ball mill apparatus (SICMBM-01). Balls to powder weight ratio, the diameter of the ball and rotation speed were kept 5:1, 1 cm and 30 RPM respectively. Afterwards, different metal powders except Mg were collected in a graphite mould. Then aluminium foil was wrapped over the mould and mould was placed in the furnace for preheating. Metal powders were
Table 2. Design matrix for screening design (Plackett-Burman Design).

| Sr. No | Stirring Speed | Stirring Time | Stirrer position | Holding Time | Holding Temperature | The particle size of reinforcement | % reinforcement | Preheating Temperature | Mould Temperature |
|--------|----------------|---------------|------------------|--------------|---------------------|-------------------------------------|----------------|-----------------------|------------------|
| 1      | 1000           | 10            | middle           | 0            | 700                 | 200                                 | 20             | 600                   | 400              |
| 2      | 1000           | 60            | bottom           | 20           | 700                 | 200                                 | 5              | 600                   | 400              |
| 3      | 200            | 60            | middle           | 0            | 850                 | 200                                 | 5              | 600                   | 0                |
| 4      | 1000           | 10            | middle           | 20           | 700                 | 800                                 | 5              | 0                     | 0                |
| 5      | 1000           | 60            | bottom           | 20           | 850                 | 200                                 | 20             | 600                   | 0                |
| 6      | 1000           | 60            | middle           | 0            | 850                 | 800                                 | 5              | 600                   | 0                |
| 7      | 200            | 60            | middle           | 20           | 700                 | 800                                 | 5              | 600                   | 400              |
| 8      | 200            | 10            | middle           | 20           | 850                 | 200                                 | 20             | 600                   | 0                |
| 9      | 200            | 10            | bottom           | 20           | 850                 | 800                                 | 5              | 600                   | 400              |
| 10     | 1000           | 10            | bottom           | 0            | 850                 | 800                                 | 20             | 0                     | 400              |
| 11     | 200            | 60            | bottom           | 0            | 700                 | 800                                 | 20             | 600                   | 0                |
| 12     | 200            | 10            | bottom           | 0            | 700                 | 200                                 | 5              | 0                     | 0                |
heated at 600 °C for 1 hour while ingots were melted at 750 °C temperature. Kongshaug et al. (2014) developed an Al-Mg/Al₂O₃ nanocomposites to find out the effect of Mg addition on porosity formation. They observed that high Mg content reduces the porosity amount by acting as a wetting agent between reinforcement particles and matrix material. Moreover, they mentioned that degassing removes unwanted gases, and thereby reduces porosity. Therefore, in the present study, degasser and flux were used to remove gases and dross respectively. Then, metal powders except Mg were poured into the aluminium melt and simultaneously stirring was performed to spread the metal powder uniformly into the melt. Meanwhile, the graphite mould was placed in the furnace for preheating at 400 °C for 20 minutes. Graphite moulds were used to cast the composite into a round bar shape. Mg was added in the mixture to improve the wettability between graphite and aluminium matrix. Fortin et al. (2009) drafted a pattern (US75626the 92B2) for the development of aluminium boron carbide composite in which they specifically mentioned that addition of Mg reduces the fluidity of the melt. Therefore, they recommended pouring of the mixture within the 20 minutes of Mg addition. Hence, in the present study, to maintain flowability of the melt, the mixture was poured into the mould within the 10 minutes of Mg addition. Degassing was performed again to remove the absorbed gases and the mixture was poured in a preheated graphite mould.

Table 3. The methodology adopted for the fabrication of the composite during the screening design.

| Run | Stirring time | Stirring Speed | Responses |
|-----|---------------|----------------|-----------|
| 1   | 10            | 600            | UTS (MPa) and % Porosity |
| 2   | 10            | 1000           |           |
| 3   | 60            | 600            |           |
| 4   | 60            | 1000           |           |

Table 4. Design matrix for 2² factorial designs.

| Run Order | Stirring time | Stirring Speed | Responses |
|-----------|---------------|----------------|-----------|
| 1         | 10            | 600            | UTS (MPa) and % Porosity |
| 2         | 10            | 1000           |           |
| 3         | 60            | 600            |           |
| 4         | 60            | 1000           |           |
After completion of the fabrication process, specimens were placed in the furnace for 2 hours at 500 °C and afterwards quenching was done in hot water at 50–80 °C. Then the specimens were placed in the open furnace at 200 °C for 2 hours. After completion of the heat treatment process, the tensile specimens were prepared as per Indian standard IS 1608 which is equivalent to ASTM B557M-10. Porosity and UTS values were measured thrice for each experimental run and average values were displayed in Table 6. Rule of the mixture was used to measure theoretical density where the Archimedean principle was used to find out measured density. As shown in Eq. (3), the percentage of porosity was obtained using the measured and theoretical densities of the composite where \( \rho_{th} \) and \( \rho_m \) show theoretical and measured densities respectively.

\[
\text{Porosity} = \frac{\rho_{th} - \rho_m}{\rho_m} \times 100
\]  

2.5. Supplementary study

The specimens as shown in Fig. 6 were prepared to compare manual and automated stirring as well as sand and permanent mould casting processes. Fluxing and degassing were used in one of the specimens to find out the effect of fluxing and degassing on surface quality, porosity, agglomeration of reinforcement particles and strength of a composite. Parameters considered for the preparation of specimens are given in Table 5. However, it is important to note that no heat treatment was given to any of the specimens. Hence, the tests were performed on as-cast specimens. Mitutoyo (SJ-210) surface roughness tester was used to measure the surface roughness of the specimen. Achard et al. (2018) suggested the use of ultrasonic inspection to

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Fig. 6. The processes used to prepare different specimen; (a) sand mould and manual stirring; (b) permanent mould and manual stirring; (c) permanent mould and automatic stirring; (d) permanent mould, automatic stirring, degassing and fluxing.
Table 5. Parameters for specimen 1, 2, 3 and 4.

| No. | Stirring speed | Stirring time | Preheating Temp. | B$_4$C (%) | Ti (%) | Gr (%) | Mg (%) | Moulding methods | Stirring methods | Other Processes                  |
|-----|----------------|---------------|------------------|------------|--------|--------|--------|------------------|------------------|---------------------|
| 1   | manual         | 12            | 600              | 10         | 0.2    | 5      | 3      | sand mould       | manual           | none                |
| 2   | manual         | 12            | 600              | 10         | 0.2    | 5      | 3      | Permanent mould  | manual           | none                |
| 3   | 650            | 12            | 600              | 10         | 0.2    | 5      | 3      | permanent mould  | automated        | none                |
| 4   | 650            | 12            | 600              | 10         | 0.2    | 5      | 3      | permanent mould, | automated        | degassing and fluxing |
speed up the process of quality control during continuous production of cast aluminium. Researchers explicitly mentioned the usefulness of ultrasonic testing for identification of locations of the flaws in cast material. Therefore, Ultrasonic Testing (UT) was carried out using Einstein-II DGS machine to locate the depth and position of the defects in cast specimen of the composite. Radiographic testing (RT) was used to explore the spot indications given by the UT. Fig. 7 shows the porosity cluster at the location identified by the ultrasonic testing for specimen 1. As shown in Fig. 8, microscopic and SEM images were taken for further validation of porosity and other defects. Likewise, Fig. 9 shows the microscopic structure of the composite obtained after automatic stirring, permanent moulding, degassing and fluxing. Cluster identification was performed by the visual inspection of the cast surface of the specimens.

3. Results and discussion

3.1. FMEA and fishbone diagram

After a literature survey and initial experimentation with composite materials, Suthar and Patel (2017) found various parameters responsible for the different characteristics of the material. Therefore, fishbone diagrams were prepared to represent all the

| Stirring Speed (rpm) | Stirring Time (min) | Predicted Value | Actual Value | %error |
|---------------------|---------------------|-----------------|--------------|-------|
|                     |                     | %Porosity UTS (MPa) | %Porosity UTS (MPa) | %Porosity UTS (MPa) |
| 650                 | 12.22               | 2.36 306.83      | 2.33 308      | 1.27 0.42 |
| 650                 | 12.22               | 2.36 306.83      | 2.40 310      | 1.69 1.03 |
| 650                 | 12.22               | 2.36 306.83      | 2.28 309      | 3.38 0.70 |

Fig. 7. Radiographic image of specimen 1.
Fig. 8. Microscopy and SEM images of porosity found in specimen 1; (a) Tensile specimen 1 after test, (b) Specimen 1 prepared for microscopy, (c) Microscopy of specimen 1 prepared, (d) SEM image of the specimen 1.

Fig. 9. Microscopy and SEM images of specimen 4; (a) cross-section of specimen 4; (b) microscopic image; (c) SEM image of specimen 4 and; (d) Enlarge portion of SEM image.
parameters irrespective of their significance. Varzakas and Manolopoulou (2017) used FMEA analysis in conjunction with cause and effect (i.e. fishbone) diagram to find out the critical points in ready to eat fruit industries and found a satisfactory result. Therefore, in the present study, FMEA analysis was performed by considering the factors from the fishbone diagram. FMEA provided the significant parameters for UTS and porosity of cast composite. Type of reinforcement, % of reinforcement, the particle size of reinforcement, preheating of reinforcement, stirring speed, stirring time, degassing, holding time, pressure and holding temperature are the significant parameters for UTS. Correspondingly, type of reinforcement, % of reinforcement, the particle size of reinforcement, preheating of reinforcement, the temperature of the liquid melt, stirring speed, stirring position, stirring time, mould temperature, degassing, holding time, mixing time, pressure, ambient temperature and holding temperature are the significant factors for porosity.

3.2. Screening design

Further sorting of parameters in the present study was performed using a Plackett-Burman design. It was used to get the most significant parameters out of the significant parameters obtained using FMEA. Some of the parameters like pressure, ambient temperature etc. that considered significant based on FMEA but not viable for the manufacturing process utilized were dropped from the list. Table 4 shows the design matrix where Figs. 10 and 11 shows the value of percentage porosity and UTS respectively for the given samples. Porosity and UTS values were measured thrice for each experimental run and average values were displayed in the graphs. Fig. 12 shows the normal effect and Pareto chars for UTS and porosity. It is evident from the graphs that stirring speed, stirring time, percentage reinforcement and preheating temperature is the most significant parameters for porosity and UTS. The Pareto chart suggests the level of significance for the significant parameters. In descending order, percentage reinforcement, stirring speed, stirring time and preheating temperature are significant parameters for porosity while percentage
reinforcement, preheating temperature, stirring speed and stirring time are the significant parameters for UTS. Normal effect plot shows the positive and negative standardized effect of the factors on responses. It is apparent from the figure that stirring speed and stirring time have a positive standardized effect on porosity while preheating temperature and percentage reinforcement have a negative standardized effect. It

**Fig. 11.** Average UTS value per sample for Plackett-Burman design.

**Fig. 12.** Pareto and Normal effect graphs for porosity and UTS for Plackett-Burman design; a) pareto chart of porosity, b) normal chart of porosity, c) pareto chart of UTS, d) normal chart of UTS.
suggests that as stirring speed and stirring time increases porosity increases while the increase in preheating temperature and percentage reinforcement decreases porosity. Similarly, increase in stirring speed and stirring time decreases UTS while the increase in preheating temperature and percentage reinforcement increases UTS.

### 3.3. Optimization design

In the end, $2^2$ factorial design was used to optimize the screened parameters for high UTS and low porosity. Fig. 13 shows graphs of UTS and porosity values per sample. Samples were fabricated as per the design shown in Table 5. It is apparent from the graphs that the increase in porosity decreases UTS which demonstrates the influence of porosity on mechanical properties. Fig. 14 shows contour and response surface plots for porosity. It is apparent from the figure that porosity reduces because of a decrease in stirring speed and time. As stirring time and speed reduced, the chance of air entrapment in the melt reduces and thereby it reduces porosity. Parizi et al. (2017) investigated the influence of manufacturing on microstructure and mechanical properties of the nanocomposite. They used stir casting for the fabrication of nanocomposite and found similar results. Similarly, Fig. 15 shows contour and response surface plots for UTS. It is evident from Fig. 15 that UTS increases with the decrease in string speed and time. Similar results were obtained by Kalaiselvan et al. (2011) when they fabricated AA6061-B$_4$C composite using stir casting method. Researchers found wettability between particles and matrix as a responsible factor for such results. The wettability assures good bonding between particles and matrix and thereby increases UTS. Moreover, Tran et al. (2018) concluded that the mechanical force applied by stirrer generates a uniform distribution of particles and thus exposes more surface area of particles for wetting. However, Gecu et al. (2017) observed that preheating of reinforcement plays a major role in wettability improvement compared to mechanical stirring. It reduces the surface tension of the reinforcement material by removing the gas layer. This improves the chances of interaction between reinforcement particles and matrix melt significantly.

![Fig. 13. (a) Average UTS and; (b) % porosity values per sample for $2^2$ design.](https://doi.org/10.1016/j.heliyon.2018.e00988)
and thereby increases wettability. Therefore, in the present study, a reduction in surface tension and an increase in wettability reflect as high UTS.

The overlying plot shown in Fig. 16 proposes the values of stirring speed (650 rpm) and stirring time (12 minutes) for desired levels of porosity (2—2.5 %) and UTS (300—310 MPa). Considering those values, confirmation tests were performed thrice and the results are shown in Table 6. It is apparent from the table that the percentage error in each conformation run is less than 5%. Therefore, it concludes that design, fabrication process and equipment are robust and capable of providing consistent results. It is apparent from the above discussion that an optimized range of stirring speed and stirring time is 600—900 rpm and 10—15 minutes respectively.
3.4. Supplementary study

Fig. 6 shows four specimens fabricated for supplementary study whereas Table 7 shows the list of various processes used for the fabrication of four specimens. All specimens were compared with one another in terms of surface roughness, particle distribution, clustering, porosity, and UTS. Fig. 8 shows microscopic and SEM images of porosity cluster present in a specimen 1. Such clusters were found throughout the length of the first specimen that constitutes a high level of porosity. This is also evident from the radiographic image of specimen 1. The increase in porosity amount reduces the mechanical strength of the material. This phenomenon is evident from the value of UTS (90 MPa) compared to other specimens. A similar result was observed by Evans et al. (2016) researchers conducted a study to find out the effect of porosity on the mechanical behaviour of biomedical polymer and concluded that porosity reduces strength significantly. Fig. 9 shows the microscopic and SEM images of specimen 4, which validates the uniform distribution of the reinforcements. Uniform distribution of reinforcement in Al-MMC improves UTS that is visible from UTS value (142 MPa) of the specimen 4. OES was performed to get the idea about the quantitative distribution of elements. Table 8 shows the chemical composition of specimen 4. It is evident from comparison between Tables 1 and 8 that specimen 4 consists of boron and carbon, which was absent in pure aluminium. Moreover, it consists of a high amount of Mg and Ti with compared to the pure aluminium. However, it is difficult to identify that the carbon percentage value...
Table 7. List of processes used for the fabrication of specimen in the supplementary study.

| Specimen no. | Combination of processes used for the fabrication          |
|--------------|------------------------------------------------------------|
| 1            | Manual stirring and sand moulding process                   |
| 2            | Permanent mould and manual stirring process                 |
| 3            | Permanent mould and automatic stirring                      |
| 4            | Permanent mould, automatic stirring, degassing and fluxing   |

Table 8. Chemical Composition of specimen 4 (values show % of each element).

|          | Al  | Si  | Fe  | Cu  | Mn  | Mg  | Zn  | Ti  | Cr  | Ni  | Pb  | B   | C   |
|----------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
|          | 92.66 | 0.445 | 0.436 | 0.012 | 0.041 | 1.256 | 0.012 | 0.08 | 0.005 | 0.008 | 0.046 | 3.561 | 1.442 |

reflects either graphite or carbide. Therefore, further validation with XRD or another test could provide qualitative information about element bonding and element distribution. Fig. 17 shows the porosity percentage, UTS, surface roughness and clustering amount for different specimens. Clustering intensity was represented with

![Graphs showing UTS, % Porosity, Surface Roughness, and Clustering Amount](https://example.com/graphs)

**Fig. 17.** (a) UTS value per sample; (b) % Porosity value per sample; (c) surface roughness value per sample and (d) clustering value per sample during the supplementary study.
numbers between one and ten where ten represents very high clustering. Porosity, surface roughness, and UTS values were measured thrice for each experimental run and average values were displayed. Fig. 17. The results show that permanent mould improves surface finish and reduces porosity up to certain extent. Further reduction in porosity is possible due to fluxing and degassing. Degasser eliminates redundant gases while flux eradicates dross from a melt. Automatic stirring improves particle distribution and thus reduces clustering. Moreover, a combination of permanent moulding, fluxing, degassing and automatic stirring improves UTS of Al-MMC. Machining was performed on the specimen 3 to authenticate that stirring provides easy access to reinforcement and thereby improves wettability. Fig. 18 shows agglomerated cluster of reinforcement after machining on specimen 3. This validates wettability between matrix and reinforcement material.

4. Conclusion

Fishbone diagram was used for graphical representation of the factors that affect responses. Type of reinforcement, % of reinforcement, the particle size of reinforcement, preheating of reinforcement, stirring speed, stirring time, degassing, holding time, pressure and holding temperature were identified as the significant parameters for UTS using FMEA analysis. Correspondingly, type of reinforcement, % of reinforcement, the particle size of reinforcement, preheating of reinforcement, the temperature of the liquid melt, stirring speed, stirring position, stirring time, mould temperature, degassing, holding time, mixing time, pressure, ambient temperature and holding temperature were found significant factors for porosity.

Furthermore, the most significant parameters from the list of significant parameters were identified using a screening design. The percentage reinforcement, stirring speed, stirring time and preheating temperature were considered significant
parameters for porosity while percentage reinforcement, preheating temperature, stirring speed and stirring time were considered the significant parameters for UTS. However, because of the unfavourable combination of parameters % porosity increased beyond 7%.

It was concluded from the optimization study that the optimized range of stirring speed 600–900 rpm and stirring time 10–15 minutes generates low porosity and high UTS for given composite. UTS improved up to 310 MPa due to an optimized range of stirring speeds, stirring time, preheating of reinforcement and heat-treatment. However, the porosity increased beyond 3% in cast composites due to excess stirring.

It was observed from a supplementary study that permanent mould reduces surface roughness below 3μm, compared to the sand casting process. The porosity reduced below 3% by degassing and fluxing. Low agglomeration was observed in specimen prepared with automatic stirring process compared to the manually stirred specimen. Compared to others, in specimen 4, UTS was improved beyond 150 MPa because of permanent mould, automatic stirring, degassing and fluxing. However, it was not improved beyond the point and absence of heat treatment was considered responsible for this phenomena.

Declarations

Author contribution statement

Jigar Suthar: Conceived and designed the experiments; Performed the experiments; Wrote the paper.
Kausik Patel: Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data.

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Competing interest statement

The authors declare no conflict of interest.

Additional information

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