Exploring the Impact of Sustainable Stir Casting Process Parameters on the Tensile Strength of AA2017-AlNp Composites: A Taguchi Technique Approach

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Abstract. By integrating sustainable materials and practices into the fabrication process of the AA2017/AlN composites, you can enhance their environmental performance and contribute to a more sustainable future for materials engineering.An attempt was made to investigate the impact of stir casting parameters on the tensile strength (TS) of AlN particles reinforced AA2017 matrix composites. The composites containing 0, 5, 10 and 15 wt.% AlN incorporated AA2017 matrix developed via stir casting route. Taguchi's L16 orthogonal design layout consisting of four input parameters and four levels were chosen to fabricate the composites. The selected process parameters were stirring time (min), stirring speed (rpm), reinforcement (wt.%) and melting temperature (oC). Similarly, the output response was considered as tensile strength (TS) and the test was performed by universal testing machine (UTM). Taguchi approach was engaged to predict the finest setting of casting parameters to achieve the superior TS of the proposed AA2017/AlN composites. The statistical results revealed that the maximum TS was produced by stirring time of 8 min, stirring speed of 500 rpm, reinforcement content of 15 wt.% and melting temperature of 700oC. ANOVA results found that reinforcement (53.95%) was the notable factor for affecting the TS, next by stirring time (37.20%). By leveraging sustainable materials and manufacturing practices, this study contributes to the advancement of environmentally friendly materials engineering practices, paving the way for a more sustainable future in the field.

Keywords: AA2017, AlN particles, Stir casting, Tensile strength, Taguchi technique.

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1 Introduction

In recent decades, the attention in discovery lighter, stronger, and new ecologically gracious materials is persistently growing as the challenges of energy shortage and grow in environmental pollution. Sustainable materials, such as recycled aluminium, bio-based composites, and advanced polymers derived from renewable sources, are gaining traction for their reduced environmental impact and potential for circularity in manufacturing processes .Aluminium alloys are utilised extensively in a broad scope of applications, including the automobile and aerospace sectors owing to their remarkable mechanical properties and light weight [1]. Traditional monolithic aluminium alloys fall short in several fields where there is a growing need for high performance. Due to its superior characteristics, aluminium alloys incorporated with different particles, also known as aluminium matrix composites (AMCs) that focus of several studies over the past decades [2, 3]. A unique combination of characteristics, including increased stiffness, greater strength, enhanced wear resistance, and a low expansion thermal co-efficient, makes AMCs a promising replacement for aluminium alloys [4]. The usage of AMCs exhibits an growing tendency in several applications including automotive, nuclear, aerospace and marine industries [5]. Among the several methods, stir casting is one of the mainly often utilised way for the development of AMCs. It is a cost effective route of creating AMCs that is suitable for bulk production. It has benefits including simplicity, versatility across an extensive range of materials, affordability, and suitability for mass production [6, 7]. Major limitations of the stir casting method such as poor wetability, aggregation and fracturing of reinforcing particles, gas entrapment, and the creation of an impurity vortex during mechanical stirring and solidifications thus lead to reduce the properties [8]. Therefore, in order to provide composites with superior qualities, appropriate selection of the stir casting factors are very essential. Farooq Muhammad et al. optimized the stir casting parameters on TS and hardness of the SiC and SiO_2 reinforced Al6063 hybrid composites using Taguchi approach. They explored the stirring time has a most noteworthy factor on TS and the hardness was mainly affected by speed [9]. Karthik et al. studied the impact of casting variables on impact strength of ZrO_2 filled AA5083 composites developed by stir casting route and they were employed Taguchi method to predict the optimal conditions for obtain the better strength [10]. Pugalenthi et al. predicted the suitable parameters on the TS of the A356 alloy composites incorporated with MoS_2 and wheat husk ash as reinforcements. They observed that the optimum variables were significantly improved the TS by 23.72% and also the stirring speed has the most beneficial impact factor on TS [11]. Rao et al. determined the tensile behaviour of SiC filled AS21 alloy composites fabricated and they stated that the higher TS of 199.35 MPa produced by the parameters were 6 wt.% of SiC, 720^{o}C of melting temperature and stirring speed of 600 rpm [12]. Divakar et al. presented the impact of casting variables on hardness and TS of Al5052 alloy composites added with Al_2O_3 and graphite as reinforcements and they revealed that the melting temperature of 750^{o}C has produced superior mechanical properties [13]. Kamaraj et al. reported the impact of variables on TS of the A356 hybrid composites and the results found that the stirring speed of 600 rpm exhibited higher TS of 247 MPa and lesser porosity of 14% [14]. Saravanan et al. presented the impact of stir casting variables on TS and hardness behaviour of the Al/RHA composites and the results depicted that the insertion of reinforcement has to be more significant trailed by stirring time and speed [15]. Jebeen Moses et al. predicted the TS of 15wt.% TiC filled AA6061 composites synthesized via stir casting technique and they were noted that TS enhances with an elevate in stirring speed and time [16]. Mohanavel et al. applied the Taguchi approach for predicting the casting variables on TS of the AA7178-Si_3N_4 composites. They noticed that the greater TS was attained by 15 wt.% of Si_3N_4 composite. They also stated that the insertion of reinforcements has notable aspect subsequently by speed [17]. Arulraj et al. studied the TS of the LM24/SiC/B_4C composites using ANOVA analysis and they noticed the stirring speed was the most predominant factor for affecting the TS [18].

Hashim Hanizam et al were derived from the nanocomposite that was exposed to DOE run 4 and contained 0.5 weight percent MWCNT, 0.5 weight percent Mg, and mechanical stirring for 10 minutes. Comparing the hardness (76.3%) and UTS (108.4%) of the alloy with the as-cast A356 alloy revealed improvements. [19].

Although numerous studies have used the stir casting method to create AMCs, only a limited studies have addressed the optimization of the process parameters. This study focuses on the stir casting method for producing AA2017/AlN composites in order to optimize the process variables. Taguchi technique was used to examine the impact of casting variables on the TS of the fabricated composites.

2 Experimental Details

In this study, AA2017 alloy was used as the base metal, while the reinforcement was used as AlN particles with mesh size of 40 microns. The composition elements of the procured AA2017 is mentioned in Table 1. This alloy widely used in aviation and automotive applications like screw machine products, pulleys and gauges, fasteners, rivets, knitting needles and crochet, etc.

Table 1 Elements of AA2017

Elements	Cu	Fe	Mn	Mg	Si	Zn	Ti	Cr	Al
Wt.%	91.5-95.5	3.5-4.5	0.4-1	0.4-0.8	0.2-0.8	0.25	0.15	0.1	Bal

Stir casting method was used to synthesize AA2017 base composites with altering proportions of (0, 5, 10, and 15 wt%) AlN particles. In casting process, there are several factors are involved. Based on the previous literatures, the properties of proposed composites mostly affected by the variables like stirring time, stirring speed and melting temperature [19, 20]. Hence, in this study these variables are selected as the input factors and are depicted in Table 2. After the selection of parameters and their levels, L16 orthogonal design formulated is shown in Table 3. At first, the measured weight of AA2017 rod was kept into a crucible made of graphite and heated to selected temperature (Table 2) in an electric furnace. The furnace was controlled by an argon gas environment to protect the casting defects during melting the alloy. The required amount of AlN particles were simultaneously warmed at 400°C to create a dry surface and strengthen the interfacial connection [21]. After that, the preheated AlN powders were added into the melt, and then the slurry was incessantly agitated with selected stirring speed and time as per Table 3. Finally, the slurry was put into a metal mould with a 25 mm diameter and a length of 150 mm. To carry out the testing, the developed AA2017-AlN composites were machined and cut into the necessary dimensions. The tensile test was conducted by UTM, and the test samples were arranged in accordance with ASTM E8 standards.

Table 2 Casting parameters and its levels

Casting parameters	Units	Levels			
		1	2	3	4
Stirring time	min	2	4	6	8
Stirring speed	rpm	200	300	400	500
Reinforcement	wt.%	0	5	10	15
Melting temperature	°C	700	750	800	820

3 Methodology- Taguchi approach

Taguchi approach is an effectual statistical tool for develop the high excellence systems. It offers a straightforward, effective, and scientific way to optimize the quality, performance, and cost [22]. In this technique, the selected input variables are formulated in a particular orthogonal design to find the best response. Here, three statistical relationships (S/N ratio) may be used in this approach to predict response [23, 24]. The objective of this research is to predict the higher TS of AA2017-AlN composites developed by stir casting method. Hence, higher the better (HB) S/N ratio relation was used to compute the TS and the Eq is given below,

$$\text{S/N ratio}[HB] = -10\log_{10}\left[\left(\frac{1}{n}\right)\left(\sum_{i=1}^{n} Yij^2\right)\right] \qquad (1)$$

where, n represents the total no. of experiments and Y represents the measured value. The computed S/N ratio value is shown in Table 3.

Table 3. L16 orthogonal design and their response

Sl. No	Stirring time (min)	Stirring speed (rpm)	Reinforcement (wt.%)	Melting temperature (°C)	Tensile strength (MPa)	S/N ratio (dB)
1	2	200	0	700	174	44.8110
2	2	300	5	750	183	45.2490
3	2	400	10	800	189	45.5292
4	2	500	15	850	211	46.4856
5	4	200	5	800	202	46.1070
6	4	300	0	850	180	45.1055
7	4	400	15	700	230	47.2346
8	4	500	10	750	226	47.0822
9	6	200	10	850	218	46.7691
10	6	300	15	800	238	47.5315
11	6	400	0	750	192	45.6660
12	6	500	5	700	232	47.3098
13	8	200	15	750	239	47.5680
14	8	300	10	700	236	47.4582
15	8	400	5	850	230	47.2346
16	8	500	0	800	193	45.7111

4 Result and Discussions

4.1 Effect of parameters on TS

Figure 1 and Figure 2 illustrates the main effect plots for S/N ratio and means of TS. From the plots, we studied the individual impact of casting parameters on TS of the fabricated AA2017-AlN composites. In these graphs, the x-axis represented in parameter levels, and y-axis denoted in S/N ratio and mean values of response. It can be noticed that the TS gradually improved with an increasing trends in AlN wt.%. The maximum TS has produced in 15 wt.% of AlN particle reinforced AA2017 matrix composite. The reason is that, the insertion of AlN act as a load bearing elements thus results in enhanced the TS. Similarly, the higher setting of stirring time and speed gives the maximum TS due to the homogeneous particles dispersion into the base alloy. The higher stirring speed increase the particle circulation which promotes the even spreading of AlN into the AA2017. Hence, the TS significantly enhanced when an raise in stirring time and speed. In meantime, the TS decreased with an decrease in melting temperature. Therefore, the maximum TS obtained in 700°C of melting temperature.

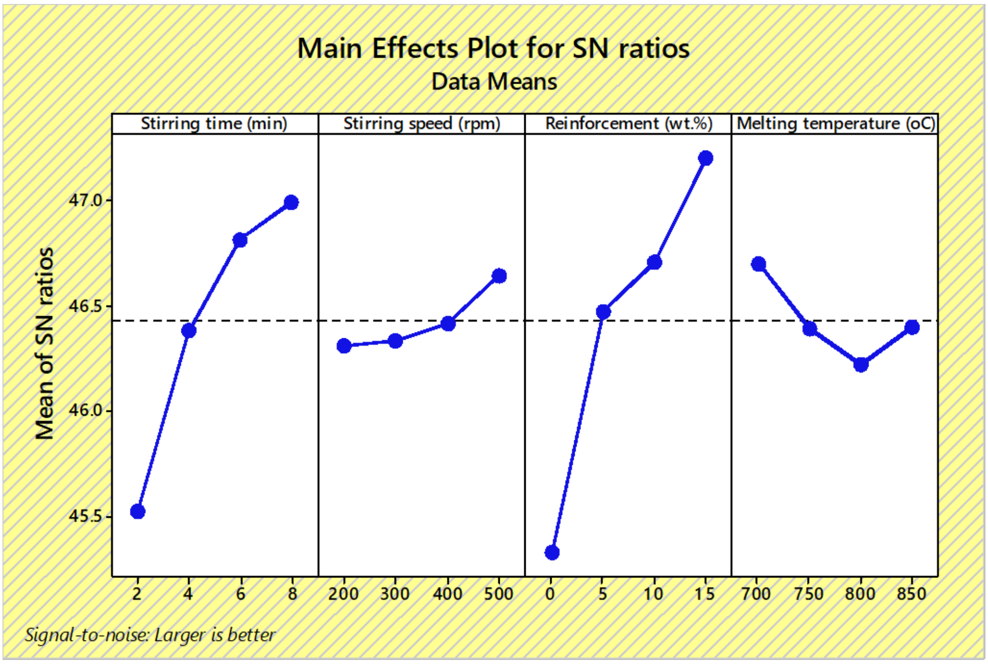

Fig. 1 S/N ratio plot of TS

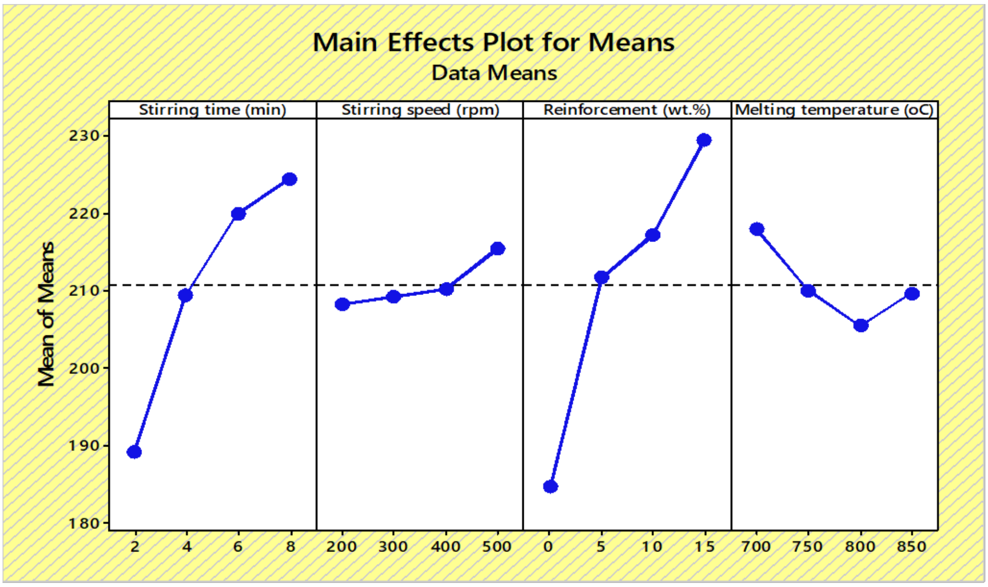

Fig. 2 Means of TS

The value of S/N ratio and mean for TS with related stir casting parameters are depicted in Table 4 and 5. It is evident from the tables that the rankings of important factors are determined. Especially, the delta value is used to determine the rank. The high and low values of the S/N ratio for each level of factor are used to calculate the delta value. The reinforcement wt.% has been shown to be the most notable impact on TS, as shown by the findings (Tables 4 and 5). The reason is behind that, the inclusion of hard AlN ceramic powders increased the TS for the produced composites. Similarly, the stirring time and melting temperature are also noticed that the more affecting factors on TS. The optimal parameter setting is taken as the higher S/N ratio value of response. As per the S/N ratio results (Table 4), stirring time at level 4 (8 min), stirring speed at level 4 (500 rpm), reinforcement wt.% at level 4 (15 wt.%) and melting temperature at level 1 (700^{o}C) were recognized as the appropriate conditions for acheiving the superior TS of the developed AA2017-AlN composites.

Table 4. S/N ratio value of TS

Level	**Stirring time (min)**	**Stirring speed (rpm)**	**Reinforcement (wt.%)**	**Melting temperature (^{o}C)**
1	45.52	46.31	45.32	46.70
2	46.38	46.34	46.48	46.39
3	46.82	46.42	46.71	46.22
4	46.99	46.65	47.20	46.40
Delta	1.47	0.33	1.88	0.48
Rank	2	4	1	3

Table 5 Mean values of TS

Level	**Stirring time (min)**	**Stirring speed (rpm)**	**Reinforcement (wt.%)**	**Melting temperature (^{o}C)**
1	189.3	208.3	184.8	218.0
2	209.5	209.3	211.8	210.0
3	220.0	210.3	217.3	205.5
4	224.5	215.5	229.5	209.8
Delta	35.3	7.3	44.8	12.5
Rank	2	4	1	3

4.2 Contour plot analysis

Figure 3 (a-f) shows the contour mapping for TS with related to casting variables. From the graphs, we understand that the interactive effect of stir casting variables such as stirring speed, stirring time, reinforcement and melting temperature on the TS of the AA2017-AlN composites. In Fig. 3(a) depict the impact of stirring speed and time on TS. It clearly noticed that the TS was greatly improved when an increases in stirring speed and time. The insertion of AlN powders uniformly scattered over the base alloy thus results in increased the TS of the synthesized composites. In Fig. 3(b) show the effect of stirring time and reinforcement on TS. It can be observed that the TS gradually raised with anincrease in stirring time and reinforcement content. Therefore, the higher TS was obtained in 15 wt.% of AlN reinforced composite by the stirring time of 8 min. Meanwhile, 10 wt.% of AlN filled composite produced the TS of 220 MPa at 6 min of stirring time.

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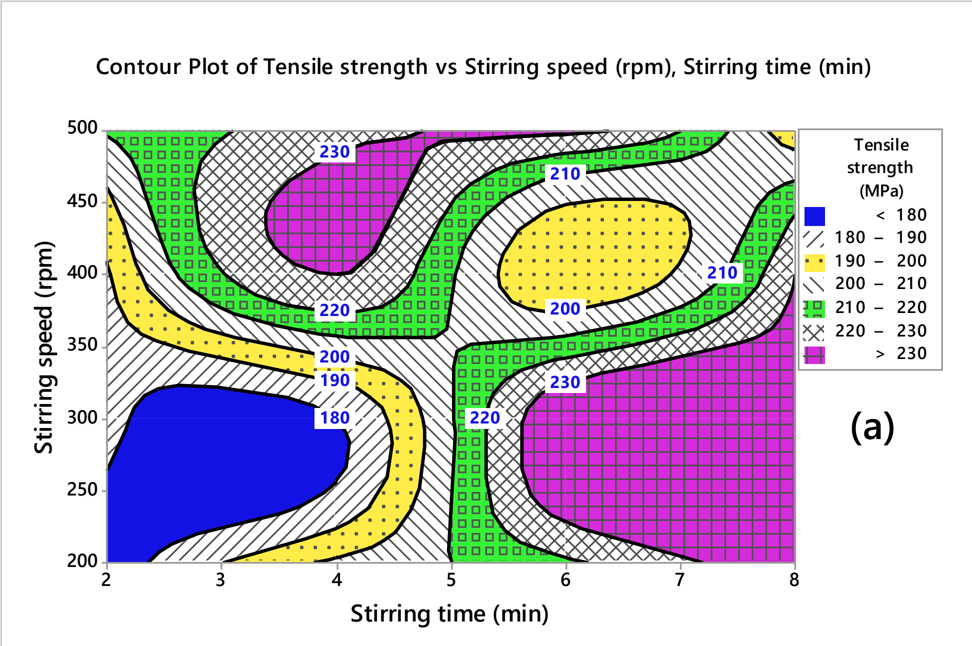

Fig. 3 (a) Stirring speed vs. Stirring time on TS

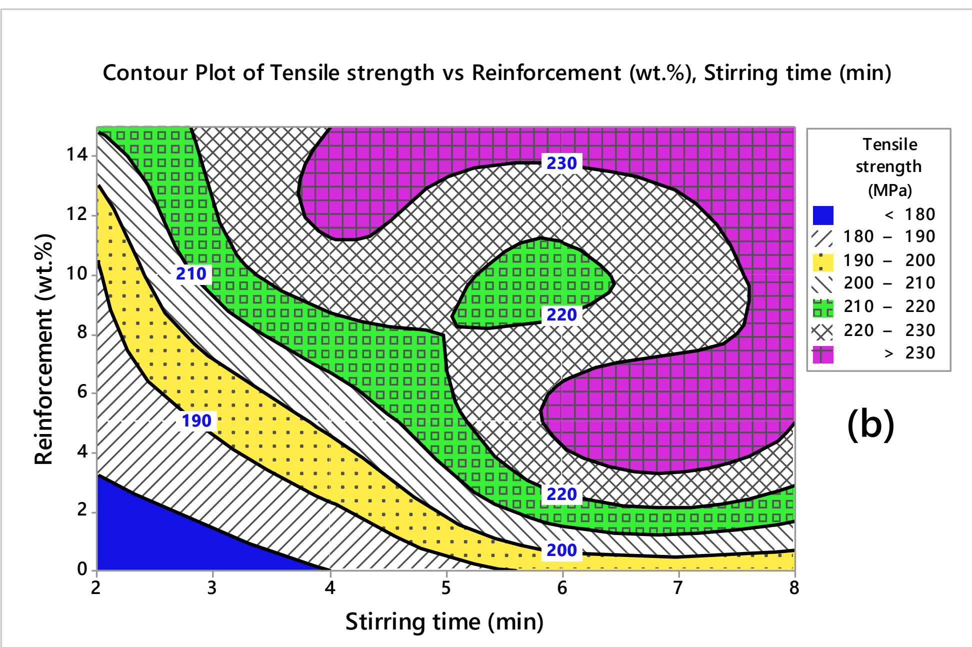

Fig. 3 (b) Reinforcement vs. Stirring time on TS

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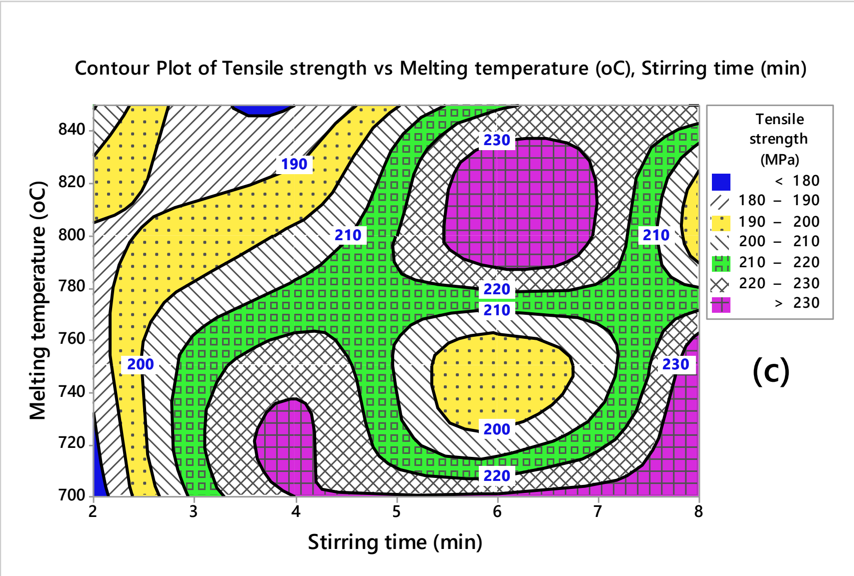

Fig. 3 (c) Melting temperature vs. Stirring time on TS

The interactive of stirring time and melting temperature on TS is explore in Fig. 3(c) It was reveal that the maximum TS of 230 MPa has been attained in 6 min of stirring time with 800^{o}C of melting temperature. Similarly, the stirring time of 8 min and 700^{o}C melting temperature achieved the higher TS 230 MPa. In mean time, the TS was steadily increased in 750^{o}C af melting temperature and stirring time of 4 min to 8 min, respectively. In Fig. 3(d) illustrate the effect of stirring speed versus reinforcements on TS. It has been evident that the less TS obtained in 0 wt.% of AlN reinforced composites at 300 rpm of stirring speed. At the same time, TS drastically increased when an increase in AlN content at 300 rpm of stirring speed. Meanwhile, the composite containing 5wt.% AlN content exhibited the maximum TS of 230 MPa at a stirring speed of 400 rpm to 500 rpm, respectively.

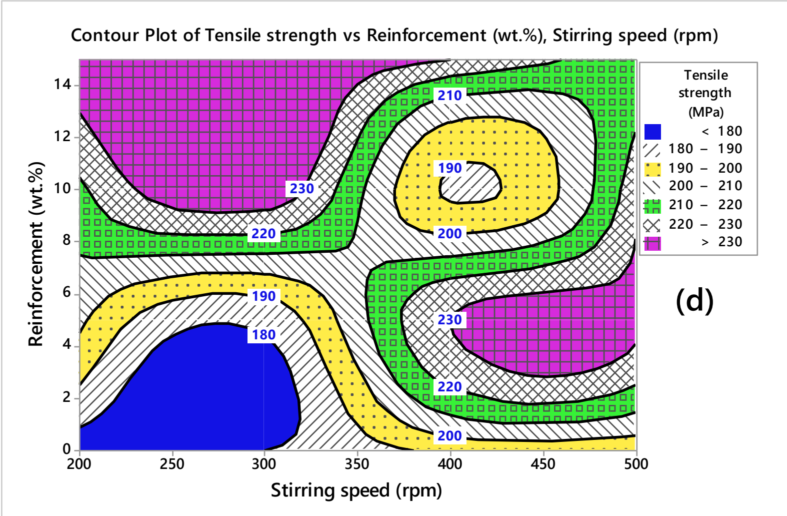

Fig. 3 (d) Reinforcement vs. Stirring speed on TS

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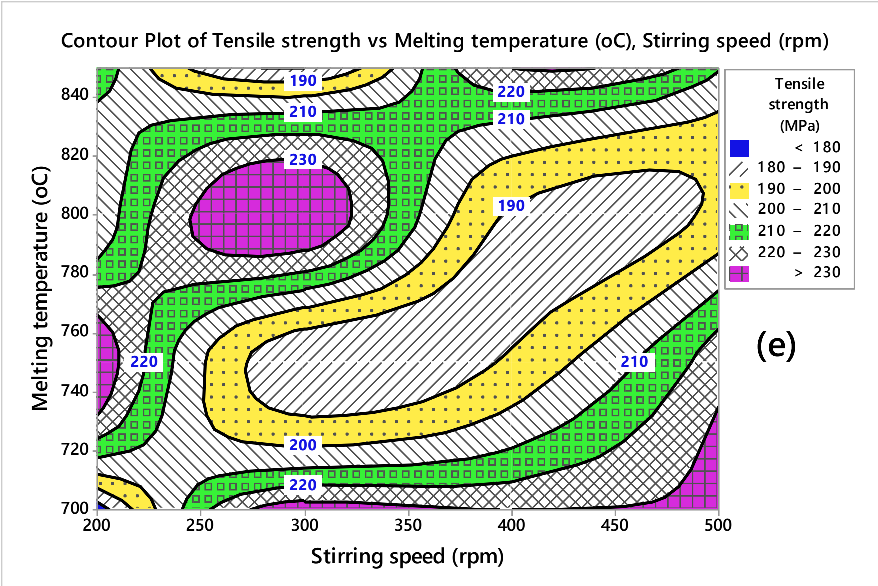

Fig. 3 (e) Melting temperature vs. Stirring speed on TS

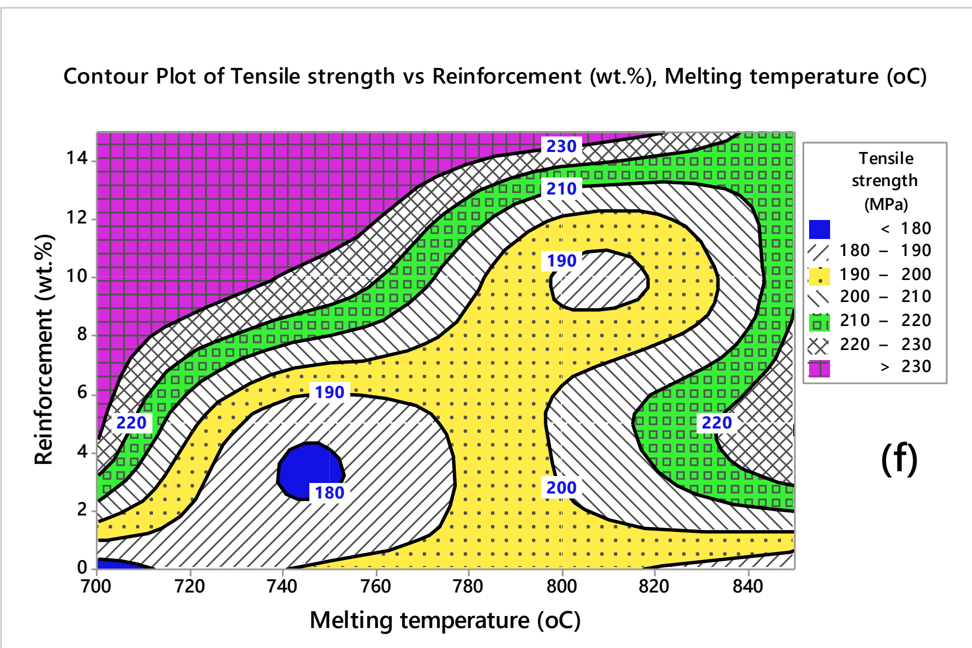

Fig. 3 (f) Reinforcement vs. Melting temperature on TS

In Fig. 3(e) reveals the impact of stirring speed and melting temperature on TS. It can be found that the higher TS attained in 750°C at a speed of 200 rpm. Similarly, the stirring speed of 300 rpm with 800°C melting temperature produced the greater TS of 230 MPa. The effect of melting temperature and reinforcement on the TS is depicted in Fig. 3(f). It can be noted that TS improved drastically when an increase in AlN wt.%. Moreover, the

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maximum TS of 230 MPa exhibited in 15 wt.% of AlN filled composite at 800ºC. However, an increase in melting temperature slightly decreased the TS from 230 MPa to 220 MPa.

4.3 ANOVA Analysis

ANOVA is employed to find the statistical impact of the independent variabless on the dependent variables [25]. Table 6 provided the result of ANOVA for TS. The F and P-values are considered to identify the impacts of variables on TS. From table 6, it was exactly noted that the F value of wt.% AlN (17.15) and stirring time (11.83) were larger than the tabulated F-value ($F_{0.05,(3,15)}$ = 3.29), hence these variables are most dominant. Likewise, the P-value of wt.% AlN (0.022) and stirring time (0.036) were less than 0.05, which are also ensured that these factors are statistical impact on TS. The contribution plot for TS is display in Fig. 4, and it was evidently reveals that reinforcement is 53.95%, which is the more significant, followed by stirring time (37.20%). The same results were found by Farooq Muhammad et al. [9]. Figure 5 display the probability plot of TS and it was ensured that the presence of residuals are exits within the limits.

Table 6 ANOVA results of TS

Source	DF	Seq SS	Adj SS	Adj MS	F	P	P (%)
Stirring time	3	2953.69	2953.69	984.56	11.83	0.036	37.20
Stirring speed	3	125.19	125.19	41.73	0.50	0.707	1.58
Reinforcement	3	4283.19	4283.19	1427.73	17.15	0.022	53.95
Melting temperature	3	326.69	326.69	108.90	1.31	0.415	4.12
Error	3	249.69	249.69	83.23	--	--	3.14
Total	15	7938.44	--	--	--	--	100
S = 9.12300; R-Sq = 96.85%; R-Sq(adj) = 84.27%							

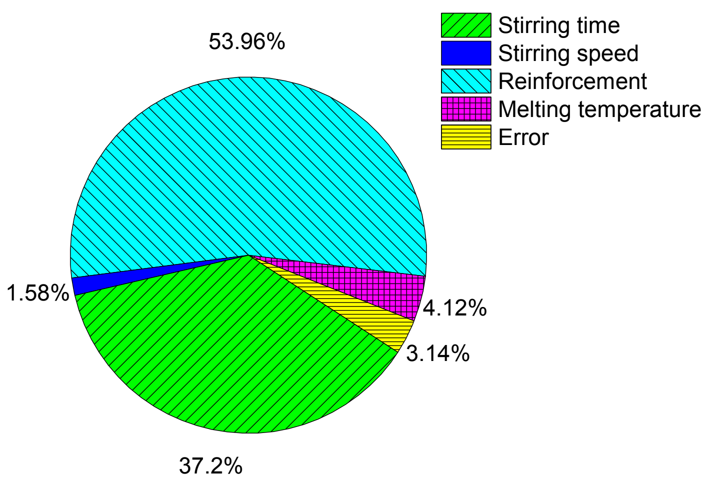

Fig. 4 Contribution plot for TS

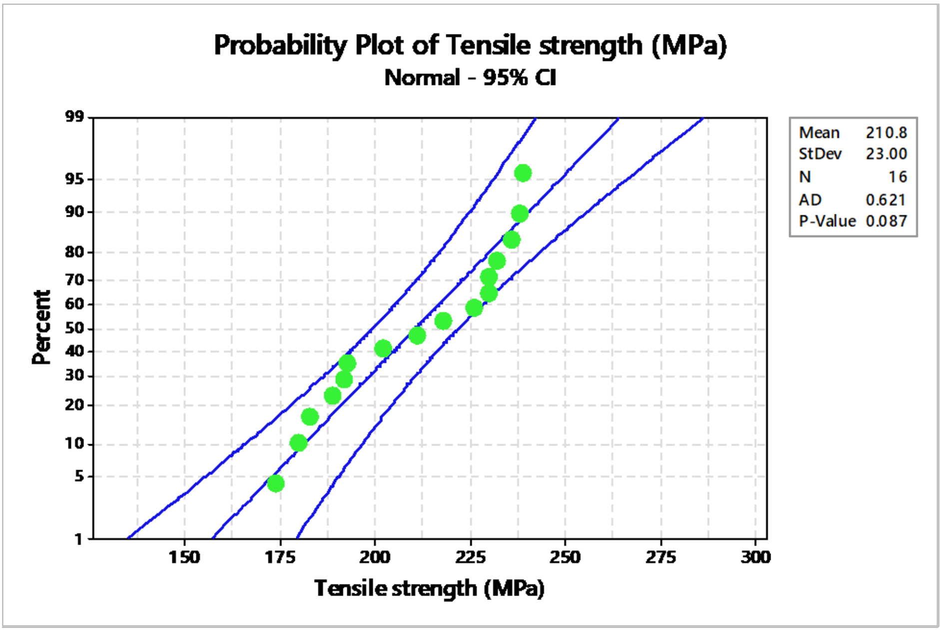

Fig. 5 Probability plot of TS

5 Conclusions

1. In this study, AA2017 matrix with varying proportions of AlN powders reinforced sustainable composites were effectively fabricated by using the stir casting route.
2. Taguchi approach was used to predict the optimum combinations of stir casting parameters for obtaining higher tensile strength (TS) of the proposed sustainable composites.
3. The experimental results explored the higher TS of the composite was achieved by the setting of optimal parameters were stirring time of 8 min, stirring speed of 500 rpm, AlN content of 15 wt.% and melting temperature of 700^{o}C.
4. ANOVA results revealed that the insertion of AlN wt.% has the dominant parameter for influencing the TS, next by stirring time having the contributions are 53.95% and 37.20%, respectively.

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