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Optimization of squeeze casting process parameters on AA2024/Al_2O_3/SiC/Gr hybrid composite using Taguchi and JAYA Algorithm

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Abstract

Squeeze castings deliver a quality product due to a large number of process parameters involved. This paper focuses on optimize the squeeze casting process parameters by using Taguchi method and JAYA algorithm. Taguchi technique was used to discover the correlation between hardness and tensile strength. Four levels and four factors such as squeeze pressure (30, 60, 100, 120 MPa), melt temperature (700, 750, 800, 850℃), die temperature (100,150,200,250℃) and pressure holding time (5, 10, 15, 20 sec) were selected for the L16 orthogonal array. JAYA Algorithm used to predict the process parameter in this research. Squeeze casting selected process parameters were considered as input variables. Hardness and tensile strength are considered as response functions. Multiple regressions were used to predict quadratic polynomial models and the obtained models were combined to a single objective.

Keywords: *Hybrid metal matrix composite; JAYA algorithm; Taguchi; Anova; Hardness, Tensile strength.*

I. Introduction

Casting is a very versatile process capable of being used in mass production. The sizes of the components vary from small to very large with intricate designs. The most important stages of the casting process are melting and solidification processes[1]. An improper processing result gives defective castings; it reduces the quality of castings in the foundry industry. Poor quality castings are due to a large number of process parameters, combined with limited automation and a shortage of skilled workers compared to the other industries[2]. Market research reveals the growing demand for aluminium based composites. The demand will further increase with effective processing methods and the prospects of recycling. Dhingra attributed the success of metal matrix composites to the savings of at least 20% over their metallic counterparts[3]. Prasad and Asthana stated that hard ceramic particles enhanced the wear resistance of aluminium alloy[4]. Composite mechanical properties such as toughness, tensile strength, hardness and ductility are greatly influenced by reinforcement size, shape and volume fraction [5]. Reduced ductility, fracture toughness and poor machinability associated with conventional MMCs can be resolved with size reinforcements. Yigezu et al. and Das et al. endorsed the selection of particulates over other shapes due to low cost and manufacturing feasibility[6]. Senthil Kumar et al. attributed the improved properties of aluminium composites to the uniform distribution of reinforcements. This can be assured by keeping the volume fraction without exceeding the critical limit[7]. The mechanical and wear properties of aluminium alloys could be considerably enhanced through the incorporation of B_4C, Al_2O_3, SiC, TiB_2, BN, Gr, and other carbonous materials in the aluminium matrix. The property enhancement primarily depends upon the selection of reinforcement type[8]. Su et al. produced AA2024/Al_2O_3 composites by semisolid casting with ultrasonic treatment. Refined grain structure, homogeneous distribution of particles and low porosity were observed with the developed composites. On comparing with unreinforced aluminium alloy, an improvement of 37% and 81% in tensile strength and yield strength were reported for 1 wt.% Al_2O_3 reinforced composite respectively [9]. The majorities of aluminium based composites are prepared through powder metallurgy and stir casting routes [10]. In the case of stir casting, high loading of nanoparticles in the melt and their uniform distribution must be ensured to meliorate the mechanical properties of composites. This demands the exploration of novel squeeze casting techniques such as casting with forging processing which reduces porosity[11]. Squeeze casting technique is a combination of the closed die forging and gravity die casting. The pressure applied in the die solidifies the melt. The functional pressure that because sudden interaction through the die

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surface generates quick heat transfer that forms a pore-free casting thereby increasing the mechanical properties of the casted product.

Casting processes such as sand casting, die casting, continuous casting, squeeze casting, investment casting are being used on a large scale. A number of input parameters govern the performance of these casting processes and hence selection of input parameters, meticulously, is important for success of these processes[12]. In order to achieve the ideal values of output parameters the researchers had used various optimization techniques for selection of input process parameters of casting processes. Taguchi technique is used to analyze the process parameters. Analysis of variance (ANOVA) is applied to evaluate the contribution percentage of process parameters of the squeeze casting. Not much of work previously reported on the addition of triple reinforcement in squeeze casting. It seems that research is still required in this direction. In this research, triple reinforcement Al_2O_3/SiC/Gr and AA2024 were selected. Materials are certain to meet the growing needs of the automobile industry. In order to improve the productivity and defects free casting, taguchi technique has used to optimize the process parameter like squeeze pressure, melt temperature, die temperature and holding time with four levels on mechanical properties of AA2024/Al_2O_3/SiC/Gr HMMC were investigated. The drawback of the previous optimization techniques, as well as the metaheuristic, and evolutionary optimizations is the possibility of merging to standards that may not be optimal but instead are trapped at a local optimal value. To comprehend this problem, a JAYA algorithm strategy is inspected in this investigation to determine the precise and optimal process parameters.

II. Experimental Procedure

AA2024 was chosen as the matrix material. Reinforcements such as Al_2O_3 (3wt. %) /SiC (3wt. %) /Gr (3wt. %) were selected. The reinforcement Al_2O_3/SiC/Gr was preheated at 450°C and reinforcements mean particle size is 10 µm has taken [7]. The squeeze casting machine setup is shown in fig.1. In that machine arrangement, the melted composite was stirred at 250rpm for 10 min; pressure has applied using hydraulic stoke.

Fig. 1 Experimental setup

To achieve the uniform distribution of reinforcement Al_2O_3/SiC/Gr are added with molten metal in the furnace and thoroughly mixed with the help of mechanical stirrer. Argon gas used to degas during casting and 1% Mg has been added during the preparation of the composite to improve the wettability of the Al_2O_3/SiC/Gr particle with the Al matrix[13].

2.1 Design of Experiments

In this work, the L16orthogonal array has been taken to study the mechanical behaviour of fabricated HMMC. Table 1 shows the considered factors and levels. The trials were calculated according to the proposed orthogonal array.

Table 1: Considered factors and levels

Factors	Character	Unit	Level 1	Level 2	Level 3	Level 4
Squeeze pressure (SP)	A	MPa	60	80	100	120
Melt temperature (MT)	B	˚C	700	750	800	850
Die temperature (DT)	C	˚C	100	150	200	250
Holding time (HT)	D	sec	5	10	20	30

Taguchi`s quality characteristics has defined in three varieties such as larger the better, nominal the better and smaller the better[14]. In this research work wear rate has considered as larger the better.

2.2 Characterizations

Vickers hardness testing machine (Shimadzu JIS Q 17025) is used to measure the composite material hardness (fig 2a). The diamond ball indenter exposed to a load of 0.5kgf for 10 sec. Hardness measured at the samples on two different positions. The average was taken on the measured hardness results.

Fig 3 shows the final cast specimens machined according to ASTM E8 standard for measuring tensile properties. Tensile properties dictate how the material reacts to forces applied in tension. The specimen is loaded in Shimadzu AG-X plus universal tester machine (fig 2b). The crosshead speed is 0.5 m/min.

Fig. 2(a) Specimen loaded on hardness tester

Fig. 2(b) Specimen loaded on UTM setup

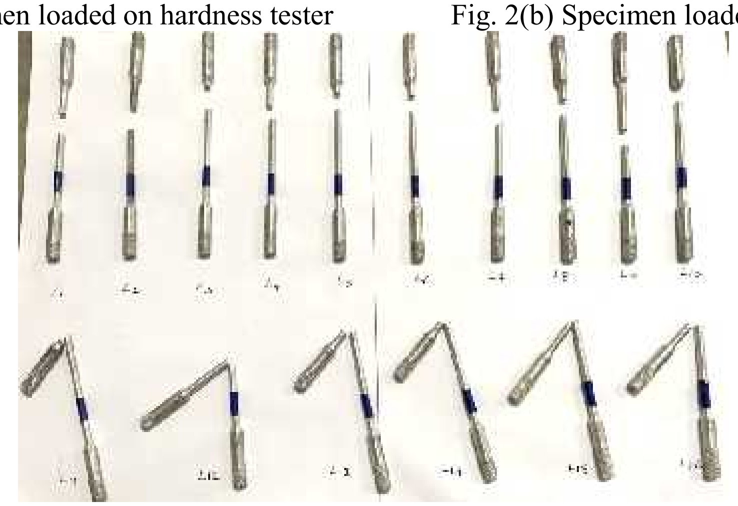

Fig. 3. Tensile specimen ASTM- E8 standard

III. Results and discussion

In this research, statistical software MINITAB-18 has been used to analyze the results. Experimental design and observed results are shown in Table 2. Signal to noise (S/N) was intended and exposed in a graphical format to understand the result of input constraints[15].

Table 2: Experimental design and results

Sample ID	SP	MT	DT	HT	HV	TS	S/N ratio for HV	S/N ratio for TS
L1	30	700	100	10	145	415	43.23	52.36
L2	30	750	150	20	147	426	43.35	52.59
L3	30	800	200	30	150	433	43.52	52.73
L4	30	850	250	40	152	422	43.64	52.51
L5	60	700	150	30	139	407	42.86	52.19
L6	60	750	100	40	144	412	43.17	52.30
L7	60	800	250	10	150	456	43.52	53.18
L8	60	850	200	20	147	432	43.35	52.71
L9	100	700	200	40	155	448	43.81	53.03
L10	100	750	100	30	163	455	44.24	53.16
L11	100	800	250	20	167	469	44.45	53.42
L12	100	850	150	10	163	451	44.24	52.81
L13	120	700	250	20	161	442	44.14	52.91
L14	120	750	200	10	156	411	43.86	52.28
L15	120	800	150	40	155	433	43.81	52.73
L16	120	850	100	30	152	420	43.64	52.46

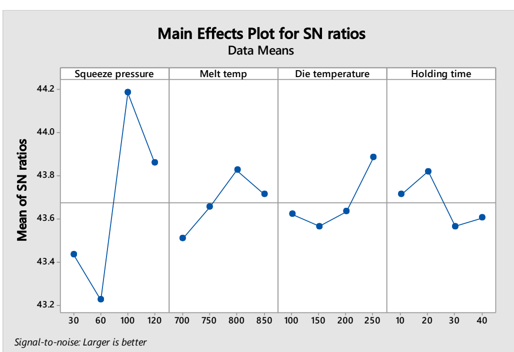

Fig. 4 S/N ratio plot for HV

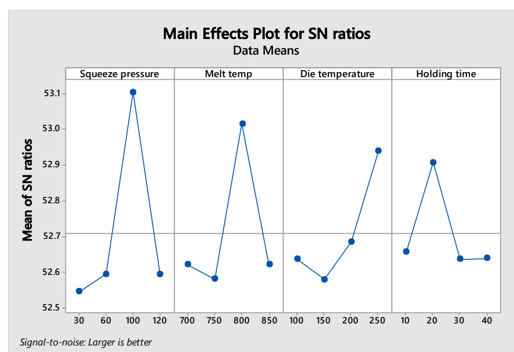

Fig. 5 S/N ratio plot for TS

Fig 4 and 5 show that the S/N ratio of squeeze pressure increases from 60 to 100 MPa and decreases from 100 MPa to 120 MPa, here that optimum squeeze pressure is 100 MPa. The melt temperature increase from 700° C to 800° C and suddenly decrease at 850° C. So that 800°C melt temperature displays optimum value. The die temperature at 250° C shows better result compare to other temperature. Pressure holding time increased up to 20 sec and decreased from 20 sec to 40 sec; thus the optimum pressure holding time is 20 sec. Table 3 and 4 show the response table for HV and TS.

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Table 3 S/N ratio response table for HV

Level	SP	MT	DT	HT
1	43.43	43.51	43.62	43.71
2	43.22	43.65	43.56	43.82
3	44.19	43.83	43.63	43.57
4	43.86	43.72	43.88	43.60
Delta	0.96	0.32	0.32	0.26
Rank	1	3	2	4

Table 4 S/N ratio response table for TS

Level	SP	MT	DT	HT
1	52.55	52.62	52.64	52.66
2	52.59	52.58	52.58	52.91
3	53.10	53.02	52.69	52.64
4	52.60	52.62	52.94	52.64
Delta	0.56	0.43	0.36	0.27
Rank	1	2	3	4

The highest hardness and tensile strength were observed at larger the better S/N values (Fig. 4 and 5). Optimum process condition obtained from the response value is A3 B3 C4 D2 for the assigned control factors signified in table 2. Optimal process parameters of hardness and tensile strength results conclude that squeeze pressures at level 3 (A3), melt temperature at level 2 (B2), die temperature at level 4 (C4) and the pressure holding time at level 2 (D2).

3.1 Analysis of Variance

ANOVA identifies squeeze process parameters that influence the characteristics of HMMC[16]. ANOVA results for hardness and tensile strength are shown in table 5, 6. In this study, it is observed that in the case of hardness, squeeze pressure has contributed majorly at a confidence level of 95%.

Table 5 ANOVA results for hardness

Source	DF	Seq SS	Influence	Adj SS	Adj MS	F-Value	P-Value
SP	3	696.75	76.59%	696.75	232.250	26.05	0.012
MT	3	62.75	6.90%	62.75	20.917	2.35	0.251
DT	3	72.75	8.00%	72.75	24.250	2.72	0.217
HT	3	50.75	5.58%	50.75	16.917	1.90	0.306
Error	3	26.75	2.94%	26.75	8.917		
Total	15	909.75	100.00%				

Table 5 shown that factors like squeeze pressure (76.59%), melt temperature (6.9%), die temperature (8%) and pressure holding time (5.58%) as the contributing to improve the hardness. The residual error has been recorded as 2.94% respectively, justifying that the investigational error involved is least and the obtained raw values are highly reliable.

Table 6 ANOVA results for tensile strength

Source	DF	Seq SS	Influence	Adj SS	Adj MS	F-Value	P-Value
SP	3	2125.3	43.46%	2125.2	708.42	9.44	0.049
MT	3	1270.3	25.98%	1270.3	423.42	5.64	0.095
DT	3	746.3	15.26%	746.3	248.75	3.31	0.176
HT	3	522.8	10.69%	522.8	174.25	2.32	0.254
Error	3	225.2	4.61%	225.2	75.08		
Total	15	4889.8	100.00%				

In table 6 shows squeeze pressure plays a significant role to achieve the tensile strength. It contributes squeeze pressure 43.46% followed by the melt temperature 25.98%, die temperature, pressure holding time with 15.26 %, 10.69% contribution and 4.61% contribution by the error. So it clearly shows that the squeeze pressure and melt temperature has the highest contribution to achieving the maximum tensile strength.

3.2 Multi linear regression equation

A comprehensive model of the regression equation was proposed using Minitab 18 software. The conventional least square method develops the equations by reducing the sum of the square residuals. Four operational parameters and four levels were considered in this study. The regression equations obtained are given below:

Hardness = 118.6 + 0.1403 A + 0.0270 B + 0.0290 C- 0.105 D……….. (1)

Tensile strength = 375.6 + 0.142 A + 0.0420 B + 0.0990 C- 0.165 D………… (2)

3.3 JAYA Algorithm

JAYA algorithm is a newly established populace-built merger technique for solving different types of optimization problems[17]. The main benefit of the JAYA algorithm matched to further evolutionary algorithms is that it is unrestricted to algorithm-specific parameters and utilizes only two common parameters that are population size and the number of iterations[18].

Regression equations has consider in this work as an objective function and it has expressed by Eq. (4) and Eq. (5),

Hardness $f(x)$ = $118.6 + 0.1403\ x_1 + 0.0270\ x_2 + 0.0290\ x_3 - 0.105\ x_4$……….. (4)

Tensile strength $f(y)$ = $375.6 + 0.142\ x_1 + 0.0420\ x_2 + 0.0990\ x_3 - 0.165\ x_4$………… (5)

Consider process parameters and their maximum, minimum ranges are expressed as follows

$30 \leq$ squeeze pressure ≤ 120

$700 \leq$ melt temperature ≤ 850

$100 \leq$ die temperature ≤ 250

$10 \leq$ holding time ≤ 40

Here, hardness f(x) and tensile strength f(y) is the objective function to be maximized and JAYA Algorithm flow chart gives detailed explanation about the process (fig 5).

3.3.1 Step for JAYA Algorithm

Stage 1: Initialize the population size (10*design variables), No. of design Variables (SP, MT, DT, HT) and no. iteration (500) till ending response attained.

Stage 2: Initialize the design variables values (maximum and minimum range)

Stage 3: Evaluate the objective function f(x) value of all combination of design parameter (maximized condition)

Stage 4: Find the X_{best} & X_{worst} from the population

Stage 5: Evaluate new value of design variables as following for all rows

$X'_{j,k,i} = X_{j,k,i} + r_{1,j,i} (X_{j,best,i} - |X_{j,k,i}|) - r_{2,j,i} (X_{j,worst,i} - |X_{j,k,i}|)$

Where r_1 & r_2 are random variables

Stage 6: Evaluate again objective functions f(x) for all rows (population size)

Stage 7: Match new & old table

Stage 8: Prepare new table with best value: if new f(X) is better than replace current row otherwise keep old row for all population size. Thus new table is prepared.

Stage 9: The process has terminated once the entire rows exposed same value. Else repeat this iteration.

Stage 10: optimum results reported [19].

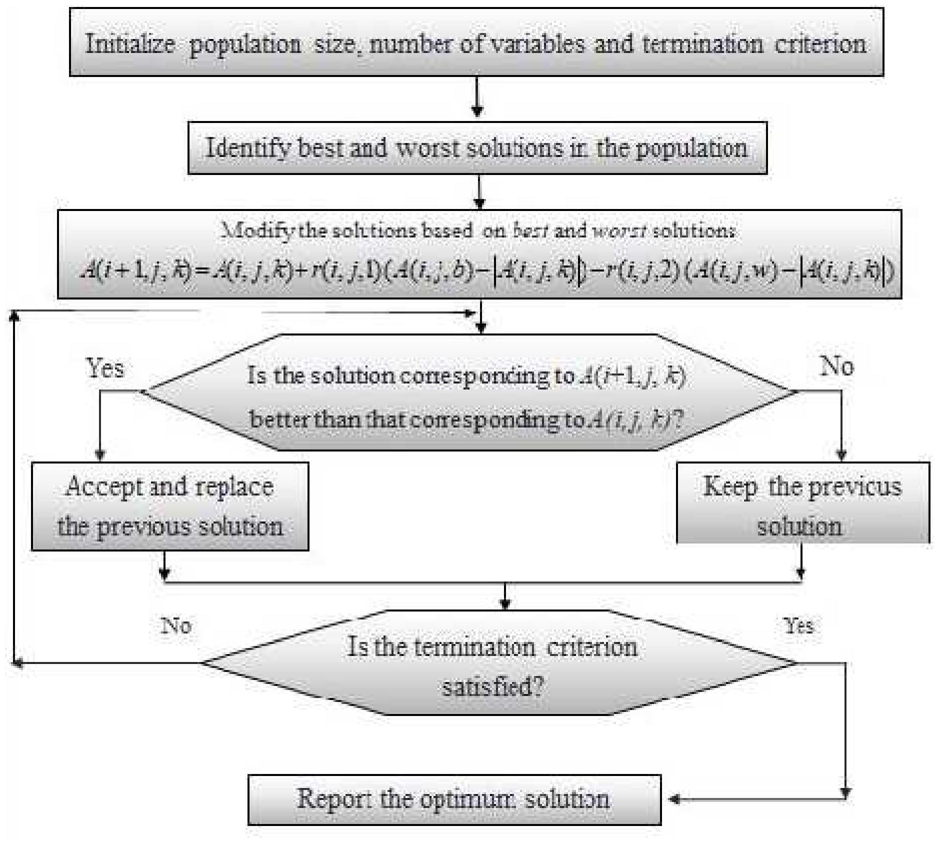

Figure 6. Flow chart of the JAYA Algorithm [20]

Hardness and tensile strength regression equations taken as a fitness function to perform the JAYA algorithm and maximize option Programme were selected. SP, MT, DT and HT has considered as design variables. The number of population has considered as 40 (10*design variables →10*4=40) and Programme runs for 500 times.

Table 7. Best solution is selected from all iteration

Iteration No	SP	MT	DT	HT	HV	TS
1	103.20	789.86	253.50	20.00	171	476
2	103.20	789.86	253.50	20.00	171	476
3	98.6651	789.00	250.65	20.00	167	472
4	96.5814	788.12	253.50	20.00	166	468
5	95.3369	787.56	253.50	19.55	165	465
6	97.2557	786.33	253.50	20.00	166	464
7	93.2589	789.86	249.87	20.00	166	462
8	96.486	789.86	249.14	19.78	166	462
9	97.6623	789.86	248.56	19.02	166	463
10	98.5987	787.23	253.50	18.94	167	465
11	101.5874	787.55	253.50	20.00	168	465
12	101.5874	786.66	253.50	20.00	168	467
13	101.4659	785.34	249.63	20.00	168	469
14	102.9821	789.86	252.85	20.00	169	471
15	103.156	789.86	253.50	20.00	170	473
16	103.20	789.86	253.50	20.00	171	476
17	103.20	789.86	253.50	20.00	171	476

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18	103.20	789.86	253.50	20.00	171	476
19	103.20	789.86	253.50	20.00	171	476
20	103.20	789.86	253.5	20.00	171	476
21	103.20	789.86	253.5	20.00	171	476
22	103.20	789.86	253.5	20.00	171	476
500	103.20	789.86	253.5	20.00	171	476

Fig 7 and 8 showed the convergence graph of hardness and tensile strength. Final optimum results were observed from 15th iteration run, after that no variations in final objective function in the consequent run. The corresponding best solution for each the iteration has mentioned in table 7. It's exposed 16th iteration onwards there is no variations on the best solution and each the iteration showed similar values in all row. This indicates termination criteria for the algorithm. Thus JAYA algorithm gets optimum value rapidly.

Figure: 7 Convergence graph of HV

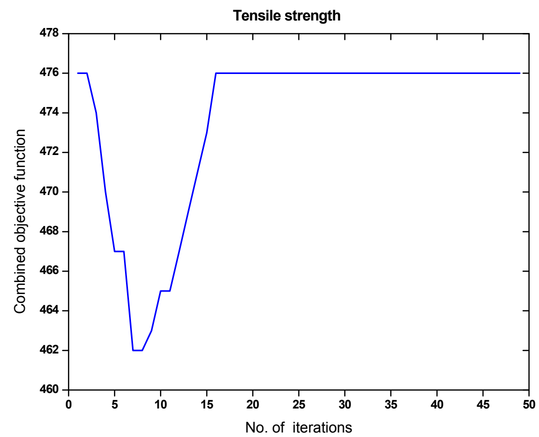

Figure: 8 Convergence graph of TS

Table 8: Comparison of the optimal values of HV and TS obtained by Taguchi and JAYA algorithm

Parameters	Taguchi method	JAYA Algorithm
Squeeze pressure (MPa)	100	103.2
Melt temp (°C)	800	789.86
Die temp (°C)	250	253.5
Holding time (Sec)	20	20.00
Hardness	167	171
Tensile strength	469	476

JAYA algorithm results indicate that SP 103.2 MPa, MT 789.86°C, DT 253.5°C and HT 20 sec showed optimum process parameters values to achieve better results. Table 8 showed a comparison of the optimal values of HV and TS obtained by Taguchi and JAYA algorithm. JAYA algorithm optimum results like hardness (171 HV) and tensile strength (476 MPa) has higher than Taguchi optimum results.

IV. Conclusion

In this research work, AA2024/Al_2O_3/SiC/Gr HMMC was successfully fabricated through the squeeze casting method. The fabricated samples were tested for hardness and tensile strength to find their relationships with process variables using the Taguchi method. JAYA algorithm successfully implemented to predicting the optimum results. The following discussions were concluding:

- A3 B3 C4 D2 such as SP 100 MPa (level 3), MT 800°C (level 3), DT 250°C (level 4) and HT 20 sec (level 2) showed optimum results in taguchi method.
- ANOVA indicated that the highest contribution percentage is squeeze pressure (HV 76.59 % and TS 43.46%).
- JAYA algorithm discovers the optimal result significantly. After 15th iteration run set of design variables very close to the optimal result.
- JAYA algorithm results shows squeeze casting process parameters such as SP 103.2 MPa, MT 789.86°C, DT 253.5°C, HT 20 sec exposed better hardness and tensile results compare than taguchi technique.

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