Process Parameter Optimization using DOE Methodology on Al- MMC to Maximize Mechanical Properties

Amneesh Singla, Shamik Shandilya, Piyush Gera, Amit Gupta

Abstract*: Metal matrix composites (MMCs) have proved their practicability as good replacements to orthodox alloys in industries like automobile, aerospace and mineral processing but the fabrication of these composites should be well regulated and optimized to have a superlative effect. The intention of this research is to optimize the stir casting process parameters to maximize mechanical properties like hardness. The matrix material used is Al7075-B4C which is optimized by DOE methodology and a mathematical model is developed. In this investigation L9 orthogonal arrays has been used through Taguchi method. The microstructures analysis of Al-B4C composite were detected by optical microscope and the hardness value is attained. The Al-MMC was fabricated by stir casting technique & the factors used in the making of composite samples were melt temperature, stirring and B4C content. The ANOVA was done to find the percent contribution of process parameters and their correlations. The effort revealed the best optimized stirring duration, melt temperature and B4C content. The B4C was found to be most imperative factor responsible for the hardness increment.

***Index Terms*: Stir casting, Al-MMC, Taguchi, ANOVA, Hardness & B4C.**

I. INTRODUCTION

Metal Matrix Composites (MMC) are engineering materials formed by metal as matrix and metal or ceramics as reinforcement to obtain a new material which has better characteristics than that of the former materials. Compared with single materials, MMC has more advantages, which have higher hardness. MMC applications on the automotive industries are used as the material of cylinder liners of engine, intake valve, exhaust valve, connecting rod, brake rotors, piston, etc. [1, 2]. Al-B4C is a MMC that can be produced by stir casting process. This process is less expensive than the other method of making process and can also be used to make complex shape components [1, 3]. Stirring in semi-solid condition can break aluminum dendrite structure when it solidified, into a small or chill-type of equi-axed structure shape.

Revised Version Manuscript Received on February 23, 2018.

Amneesh Singla, Assistant Professor, Department of Mechanical Engineering, University of Petroleum and Energy Studies, Dehradun (Uttarakhand)-248007, India.

Shamik Shandilya, Student, Department of Mechanical Engineering, University of Petroleum and Energy Studies, Dehradun (Uttarakhand)-248007, India.

Piyush Gera, Student, Department of Mechanical Engineering, University of Petroleum and Energy Studies, Dehradun (Uttarakhand)-248007, India.

Amit Gupta, Student, Department of Mechanical Engineering, University of Petroleum and Energy Studies, Dehradun (Uttarakhand)-248007, India.

Ceramic particles condition with small grain size matched with small aluminum structure can enforce Al-B4C composite [4]. Stirring can also increase distribution of B4C particles in aluminum matrix [5]. Non-uniform distribution of B4C particles on the matrix caused MMC Al-B4C mechanical properties become inferior compared with uniform distribution particles. Porosity is a smooth holes defect created by gas which is trapped during mixing process with stirring and shrinkage during solidification. The coarser B4C reinforcement particle size will make the bigger Al-B4C composite porosity [9]. The aim of this research is to optimize the process parameters of stir casting by Taguchi method for maximizing the hardness of Al-B4C composites. This research also aims to analyze the effects of process parameters on the hardness of Al-B4C.

II. MATERIALS AND METHODS

A. Materials

Composite materials used Al-7075 alloy as a matrix and B4C (Boron carbide) particles of 400 mesh size (32 μm) as reinforcement agent. Chemical compositions of the Al-7075 alloy ingot (% wt.) were 5.6–6.1% zinc, 2.1–2.5% magnesium, 1.2–1.6% copper, Morphology of B4C particle forms were angular. The Al-7075 alloy materials were supplied by Aerospace metals private Limited, Pune, India and the B4C particles were supplied by Geepax limited, Noida, India.

B. Stir Casting Process of Al-B4C Composites

The Al-7075 alloy was heated up in a graphite crucible in a resistance furnace until the above melting point (above 680 oC) to make sure that the Al-7075 alloy was perfectly melted, before it mixed with B4C particles. The Al-7075 alloy was heated at temperature of 500 oC with holding time of 2 hours. At the same time, B4C particles were also heated up at temperature of 500 oC with holding time of 2 hours before they were mixed with Al-7075 alloy to eliminate the water vapor from its surface [6]. The melted Al-7075 alloy mixed with B4C particles by stirring process. The stirring was conducted to obtain evenly distribution of B4C particles in aluminum matrix. Stirring process was conducted in two steps, which were stirring in a slurry condition (on temperature of 580 oC).

Published By:
Blue Eyes Intelligence Engineering
& Sciences Publication Pvt. Ltd.

For 30 minutes with rotation speed of 600 rpm and stirring on melted condition according to process parameters in Table 1. Process parameters and factors used in this experiment were B4C content of 2, 3.5, 5 % (wt.), melting temperature of 700, 750, 800 oC and stirring duration of 10, 15 and 20 minutes. The Al-B4C composites molten then were poured into a steel mold which pre-heated at temperature of 200 oC [8]. The Al-7075 composites formed in the mold were solidified and cooled for 2 hours, before taken out from the mold. Schematic diagram of Al-B4C composites stir casting process is shown in Figure 2.

C. Brinell Hardness Test

Hardness of Al-B4C composite was obtained by using Brinell hardness testing machine. In this case, the specimens were pressed with 5 mm diameter steel ball with normal load (F) of 250 N. The Brinell hardness value (HB) was determined by using the following the equation 1. [10]

$$HB = \frac{2F}{\pi D\left(D - \sqrt{D^2 - d^2}\right)} \quad (1)$$

Where HB, F, D and d are Brinell hardness (kg/mm2), test force (kg), diameter of the ball (mm), and mean diameter of the indentation (mm) respectively

D. Taguchi Experimental Design

Experimental designs used a Taguchi method standard. The factors and level or variation used in these experiments were shown in Table 1.

Table 1: Experimental Factors and Parameters Variation

PARAMETERS VARIATION				
	Experimental factors	1	2	3
X1	B4C content (wt. %)	2	3.5	5
X2	Melt Temperature(oC)	700	750	800
X3	Holding Time(minute)	10	15	20

There were 3 experimental factors with each 3 level or variation, so the degree of freedom of total experiment were 9. Based on number of experimental factors, number of variation and number of degree of freedom, experimental design standard according to Taguchi method was L9 orthogonal arrays (in Table 2).

Based on Taguchi method, Brinell hardness test data in each experiment were converted using equation 2. [11]

SIGNAL-TO-NOISE: Larger is better

$$S/N = -10 * \log\left(\Sigma\left(1/Y^2\right)/n\right) \quad (2)$$

Where S/N ratio, n and Y are signal to noise ratio (dB).

Table 2: L16 Orthogonal Array Design

Experiment	%B4C (X1)	Melt Temperature (X2)	Holding Time (X3)
1	2	800	10
2	2	700	15
3	2	750	20
4	3.5	800	15
5	3.5	700	20
6	3.5	750	10
7	5	800	20
8	5	700	10
9	5	750	15

III. RESULTS AND DISCUSSIONS

A.Brinell Hardness

The result of the Brinell hardness test and the S/N ratio for each experimental are shown in Table 3.

Table 3: Experimental Condition and Results

Experiment	%B4C	Melt Temperature (oC)	Holding Time (Min.)	Brinell hardness average (kg/mm2)	S/N ratios (dB)
1	2	800	10	89.075	38.9724
2	2	700	15	88.575	38.9251
3	2	750	20	121.775	41.6053
4	3.5	800	15	100.800	40.0461
5	3.5	700	20	123.525	41.5080
6	3.5	750	10	99.350	39.9119
7	5	800	20	130.625	42.1463
8	5	700	10	88.600	38.9212
9	5	750	15	124.450	41.6777

Response data of Brinell hardness test were calculated to make Brinell hardness response and S/N ratio tables. Data calculations used MINITAB 16 and excel software. The results of experiment data calculations were shown in Table 4 and Table 5.

Table 4: Response Table for Means of Brinell hardness number

Level	%B4C	Melt temperature	time
1	99.81	100.23	92.34
2	107.89	115.19	104.61
3	114.56	106.83	125.31
Delta	14.75	14.96	32.97
Rank	3	2	1

Table 5: Response Table of S/N ratios-larger is better

Level	%B4C	Melt temperature	time
1	39.83	39.78	39.27
2	40.49	41.06	40.22
3	40.92	40.39	41.75
Delta	1.08	1.28	2.48
Rank	3	2	1

Rank order of factors affecting Brinell hardness of Al-B4C composites were B4C content, melting temperature and holding time (Table 4). ANOVA (Analysis of variance) as shown in Table 6 and Table 7 indicated that the most significant factor affected on the Brinell hardness is Holding Time with probability value of P = 0.05 for level of confidence 95 %.

Table 6: Analysis of Variance of Brinell hardness Average

Analysis of Variance for Means

Source	DF	Seq SS	Adj SS	Adj MS	F	P
%B4C	2	327.3	327.3	163.67	2.76	0.266
Melt temperature	2	337.2	337.2	168.59	2.85	0.260
time	2	1665.8	1665.8	832.88	14.06	0.050
Residual Error	2	118.5	118.5	59.23		
Total	8	2448.7				

Where DF, Adj SS, Adj MS, F and P are degrees of freedom, the sum of squares, the mean sum of squares, the F-ratio and factor probability respectively. Contribution (%) is percentage contributions of factor on the Brinell hardness of Al-B4C composite.

Table 7: Analysis of variance of S/N ratios

Analysis of Variance for SN ratios

Source	DF	Seq SS	Adj SS	Adj MS	F	P
%B4C	2	1.7783	1.7783	0.8891	3.94	0.202
Melt temperature	2	2.4612	2.4612	1.2306	5.45	0.155
time	2	9.4341	9.4341	4.7170	20.90	0.046
Residual Error	2	0.4514	0.4514	0.2257		
Total	8	14.1249				

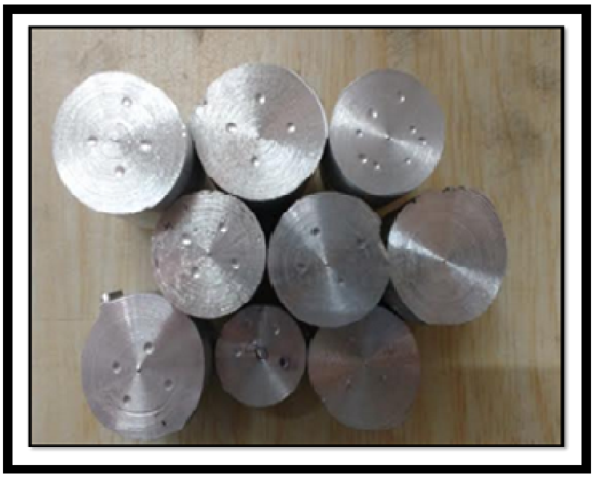

Figure 1: Hardness Test Samples

B. Effect of Process Parameters on Brinell hardness

The effect of Process Parameters on Brinell hardness and S/N ratio are shown in Figure 3 and Figure 4 respectively.

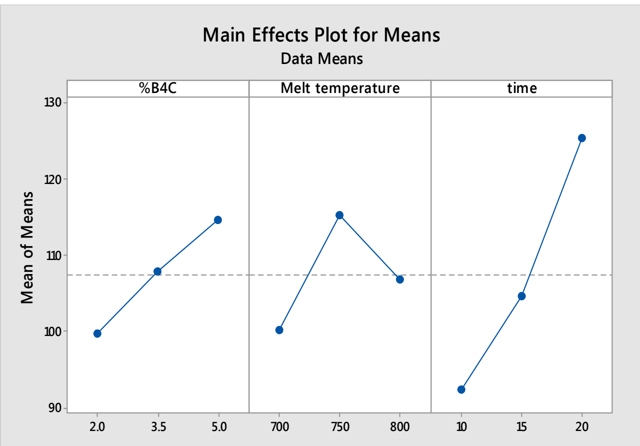

Figure 3: Effect of Process Parameters on Brinell hardness

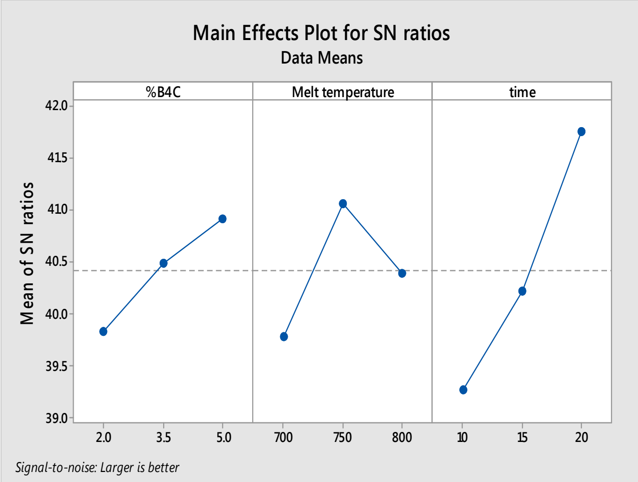

Figure 4: Effect of Process Parameters on S/N ratios-larger is better

C. Effect of B4C content on Brinell hardness

The effect of B4C content on Brinell hardness and S/N ratio are shown in Figure 3 and Figure 4 respectively. In Figure 3, it is shown clearly that the increasing of B4C content parameter from 2 to 5 % (wt.) on Al-B4C composite produced by stir casting technique is able to increase the average Brinell hardness of 14.78 %. Brinell hardness of Al-B4C composite increases from 88.575 to 130.625 kg/mm2. The highest S/N ratio is on variation 3 (40.92 dB) with B4C content of 5 % (wt.). So the optimum Brinell hardness of Al-B4C composite is obtained on parameter condition of B4C content of 5 % (wt.). The composite Brinell hardness increases because the addition of B4C particles which were spread on the aluminum matrix. The hardness of B4C particles is higher than the hardness of aluminum matrix, therefore the increasing of B4C particles content on aluminum matrix produces the increasing of composite hardness. This result (Figure 3) is consistent with the studies conducted by Kayal et al [12] and Behera et al [13], their study results stated that the Brinell hardness of Al-SiC composite increased by increasing of SiC content on the matrix of aluminum alloy LM6 (Al-10-13 % Si, in weight %). Our result is also consistent with the studies conducted by Malau et al [14], it stated that increasing of SiC content parameter from 0 to 15% (wt.) on Al-SiC composite produced by stir casting technique is able to increase the average Brinell hardness of 16.94 %. This is reliable because SiC being hard covalently bonded material share similar property with B4C being the third hardest material [15].

D. Effect of Melt Temperature on Brinell hardness

The effect of parameter variation of melting temperature factor on Al-B4C composite hardness is shown in Figure 3. Based on Figure 4, it is shown clearly that increasing melting temperature from 700 to 800 oC is able to increase Brinell hardness of Al-B4C composite by 15 % from 850-900 oC and decreasing from 750-800 oC by 7.9%. This shows that Brinell hardness of Al-B4C composite increase from 700-750 oC and decreases from 750-800 oC the highest effect of melting

Published By:
Blue Eyes Intelligence Engineering
& Sciences Publication Pvt. Ltd.

Temperature on S/N ratio is on second variation (41.06 dB). At 750 oC high value of hardness is obtained which is attributed to the accumulation of B4C particles due to changes in viscosity of molten matrix. The viscosity of aluminum matrix decreases with increased temperature and ultimately increases the incoherency of the reinforced particles within the matrix. [16]. Thus due to high temperature incoherency between the matrix and reinforcement increases which in-turn decreases the bond strength and hence the hardness of composite decreases.

E. Effect of Holding Time on Brinell hardness

The effect of holding time duration on Brinell hardness of Al-B4C composite is shown in Figure 3. Based on Figure 3, the increasing duration of holding time 10 to 20 minutes can increase Brinell hardness of Al-B4C composite from 92.341-125.30 kg/mm2, Highest S/N ratio is on time duration of 20 minute with value of 41.75 dB, so the optimum hardness of the composite happened in the time duration should be of 20 minutes condition. Therefore holding time is the most significant factor according to response table and ANOVA table of means and S/N ratio. Having the probability value P= 0.05 for level of confidence of 95%. The addition of B4C particles in the matrix prompts much strength to matrix alloy by offering more resistance to tensile stresses. It is well acknowledged that the thermal expansion coefficient of B4C particle is 5 x 10-6 / oC and for aluminum alloy is 23 x 10-6 / oC. The thermal mismatch between matrix and the reinforcement sources higher dislocation density in the matrix and load bearing capacity of the hard particles which subsequently increases the composites strength [17]. Thus, At 20 minutes of holding time highest hardness is observed. Many researches have also reported that the value of hardness decreases with holding time more than 20 minutes. This can be attributed to the porosity formation in the liquid matrix due to vortex formation which entrap the gases inside the matrix [18].

IV. CONCLUSIONS

The analysis of the effect of parameters on Al-B4C composites hardness using Taguchi method has shown very good results.

- Increasing parameter of B4C content factors to 5 % (wt.) and melting temperature to 750 oC are able to increase the composite hardness made by stir casting process.
- The best duration of holding time is 20 minutes and is the most significant factor for hardness of composite.
- The optimum process parameters are B4C content of 5 % (wt.), melting temperature of 750 oC and holding time of 20 minutes according to the experiment.

ACKNOWLEDGMENTS

The authors gratefully acknowledge the support provided by University of Petroleum and Energy Studies, Dehradun for helping us to use lab facilities for the research work. I sincerely thank all the faculties and laboratory assistants for guiding and supporting for the work without them the research would not have been possible.

REFERENCES

1. Hort, N., & Kainer, K. U. (2006). Powder Metallurgically Manufactured Metal Matrix Composites. Metal Matrix Composites: Custom-made Materials for Automotive and Aerospace Engineering, 243-276.
2. Surappa, M. K. (2003). Aluminium matrix composites: Challenges and opportunities. Sadhana, 28(1-2), 319-334.
3. Chawla, K. K., & Chawla, N. (2014). Metal Matrix Composites: Automotive Applications. Encyclopedia of Automotive Engineering.
4. Hashim, J. (2001). The production of cast metal matrix composite by a modified stir casting method. Jurnal teknologi, 35(A), 9-20.
5. Bhushan, R. K., & Kumar, S. (2011). Influence of SiC particles distribution and their weight percentage on 7075 Al alloy. Journal of materials engineering and performance, 20(2), 317-323.
6. Naher, S., Brabazon, D., & Looney, L. (2007). Computational and experimental analysis of particulate distribution during Al–SiC MMC fabrication. Composites Part A: Applied Science and Manufacturing, 38(3), 719-729.
7. Ravi, K. R., Pillai, R. M., Pai, B. C., & Chakraborty, M. (2007). Influence of Interfacial Reaction on the Fluidity of A356 Al-SiCp Composites—A Theoretical Approach. Metallurgical and Materials Transactions A, 38(10), 2531-2539.
8. Aqida, S. N., Ghazali, M. I., & Hashim, J. (2004). Effects of porosity on mechanical properties of metal matrix composite: an overview. Jurnal Teknologi, 40(A), 17-32.
9. Jit, N., Tyagi, A. K., Singh, N., & Singh, A. (2011). Comparison of Porosity and Density for (A384. 1) 1-x [(Reinforcement) p] x MMC System Using Adaptive Neuro-Fuzzy Inference System. Advances in Applied Science Research, 2(4), 240-250.
10. ASTM International, 2003, "Annual Book of ASTM Standards", Section 3: Metals Test Methods and Analytical Procedures, Volume 03.01, Designation: E10-01.
11. Belavendram, N. (1995). Quality By Design: Taguchi Technique for Industrial Experimentation. Experimental Quality: a strategic approach to achieve and improve quality, 47-72.
12. Kayal, S., Behera, R., Nandi, T., & Sutradhar, G. (2011). Solidification behavior of stir-cast Al alloy metal matrix composites. International Journal of Applied Engineering Research, 2(2), 350.
13. Behera, R., Das, S., Chatterjee, D., & Sutradhar, G. (2011). Forgeability and machinability of stir cast aluminum alloy metal matrix composites. Journal of Minerals and Materials Characterization and Engineering, 10(10), 923.
14. Malau, I. V., Wildan, I. M. W., & Suyitno, S. T. (2015). Pengaruh Parameter Proses Pengecoran Stir Casting Pada Sifat Fisis dan Mekanis Komposit Al-SiC (Doctoral dissertation, Universitas Gadjah Mada).
15. Pierson, H. O. (1996). Handbook of refractory carbides and nitrides: properties, characteristics, processing and applications. William Andrew.
16. Sozhamannan, G. G., Prabu, S. B., & Venkatagalapathy, V. S. K. (2012). Effect of processing paramters on metal matrix composites: stir casting process. Journal of Surface Engineered Materials and Advanced Technology, 2(01), 11.
17. Kalaiselvan, K., Murugan, N., & Parameswaran, S. (2011). Production and characterization of AA6061–B4C stir cast composite. Materials & Design, 32(7), 4004-4009.
18. Amirkhanlou, S., & Niroumand, B. (2011). Development of Al356/SiCp cast composites by injection of SiCp containing composite powders. Materials & Design, 32(4), 1895-1902.