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Optimization of powder metallurgy parameters of TiC and B_4C reinforced aluminium composites by Taguchi method

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Abstract

In this paper, the aluminium based metal matrix composite material has been developed via powder metallurgy (PM) route by considering the various input process parameters. Sintering time, sintering temperature and compaction pressure are the three main factors used as input process parameters which are varied at three levels. Investigations have been planned with reference to the experimental design of L9 orthogonal array using a 3x3 matrix. The density, Vickers hardness and compression strength are experimented and analyzed. The influence of individual input parameters has been analyzed using Taguchi based S/N ratio and analysis of variance (ANOVA). The optimum parameter levels to achieve less density, high hardness and high compressive strength were identified through the main effect plots. Experimental results indicate that the sintering temperature and compaction pressure highly influences properties such as density and hardness. Similarly, compression strength mainly depends on sintering time and sintering temperature. Through ANOVA analysis, it was also confirmed that the selected parameter levels of the optimum sintering

time at an average compaction pressure and sintering temperature will produce the best metal matrix composite material.

Keywords: Composite, Hardness, Density, Compression strength, Taguchi method.

1. Introduction

Researches in the composite have been increasing and it has produced tremendous solutions for many complex problems. Still, the requisition for alternate material in structural conditions is not fulfilled (Karl U. Kainer 2006). The selection of composite material and the process used for the development of composite material is still striving and challenging. The metal matrix composite (MMC) and polymer matrix composite (PMC) are the two main leading materials used in many engineering applications (Matthews and Rawlings 1999; Daniel Gay 2014). The aluminium based metal matrix composite (AMMC) is one of the excellent engineering materials that are most commonly used for structural applications. Aluminium based composites are considered to be the best alternative for conventional metals due to their characteristics such as high strength, lightweight and great wear-resistance property (Purohit et al. 2012; Torralba et al. 2003; Clyne and Withers 1995). Aluminium based composites are soft in nature, impermeable, affordable, easy to manufacture complex geometry of the component and also possess good thermal and electrical conductivity (Karl U. Kainer 2006). These metal matrix composites possess high resistance towards vibration damping and chemical/ electrochemical corrosion (Bodunrin et al. 2015). To enrich the metallurgical properties and also to increase the mechanical properties of the composite, fillers and reinforcements has been included. At the same time, the process adopted in the manufacturing of metal matrix composite will also be influenced in enriching the properties.

Powder compaction is a common method adopted to develop aluminum–based metal matrix composite material (Donnell et al. 2001). Literatures are available to discuss on reinforcement of hard reinforcement particle and aluminium matrix material (Umasankar et

al. 2014; Guo et al. 1996; Mohanasundaram et al. 1996; Ling et al. 1995). Especially, the combination of Al matrix with SiC, B_4C, silica sand, TiC, MgO, Al_2O_3, TiO_2 and other reinforcements have been extensively investigated and flooded out for wide applications (Anil Kumar Bodukuri et al. 2016; Nassar and Nassar 2017; Sannino and Rack 1995; Chou et al. 2007; Roshan et al. 2013; Samer et al. 2015). Though several experimentations have been undergone by the researchers with many new reinforcements, B_4C and TiC has attracted the researchers because of their inherent properties. The application areas of B_4C reinforced Al composites include armour tanks, bullet-proof jackets and aircraft joint parts. TiC reinforced Al composites are widely used in automotive parts such as liners for engine cylinders, piston and engine frames because of their high thermal stability and damping strength due to their excellent wear properties (Suresh Kumar et al. 2014; Ahamed et al. 2010; Karantzalis et al.1997; Sangita Mohapatra et al. 2016). In addition to high hardness, B_4C and TiC also have remarkable properties such as low density, high strength, good wear resistance and good chemical stability (Mohanty et al. 2008; Shorowordi et al. 2003; Sonber et al. 2013; Anandkumar et al. 2012; Patidar and Rana 2017; Pushpanathan et al. 2020). While increasing the weight proportion of hard particle reinforcement, the inherent mechanical properties are dropped down. Chennakeshava Reddy and Essa Zitoun (2010) have reported the mechanical properties of composites with different Al grade matrix materials and 20% SiC reinforcement. The metallurgical structure of the Al-SiC composites with a maximum weight percentage of SiC, will be heterogeneous in nature and it may lead to severe mechanical failure in sudden applications (Habibur Rahman and Mamun Al Rashed 2014). It has been observed that the hardness and ductility decrease on varying the weight percentage (in increasing mode) of reinforcement (Surappa 2003). Al MMCs reinforced with B_4C reinforcement can alone produce required properties and metallurgical quality with appropriate process parameters (Shi et al. 2012; Casati and Vedani 2014). Hybrid composites

are obtained by combining the matrix material with two or more different properties of reinforcements. These hybrid composites gain importance over single reinforced composites (Singh and Chauhan 2016; Jeng et al. 1992; Chandrakanth et al. 2010).

From the discussed works of literature, it has been identified that ample research work has been done to develop MMC material. In the present work, different combinations of reinforcement and mechanical properties evaluation are the major focus.

There is a scope to apply this metal matrix composite material in electrochemical applications also. Therefore, it has been planned to develop Al+TiC+B_4C aluminium based hybrid MMC with dominating mechanical and electrochemical properties. In the present investigation, the weight proportions of Al, TiC and B_4C are made to be constant and the processing of MMCs is made at different conditions. Thus, the prepared composites have been subjected to the evaluation of mechanical properties. Further, the metallurgical surface characterization has also been planned to infer the quality of the proposed composite material for environmental responsive structural applications.

2. Experimental Methodology

2.1 Processing of composite material

For the proposed work, the matrix material aluminium was reinforced with TiC and B_4C. Commercially available in aluminium powder with a 99.9% purity and of size 300-320 μm has been procured for processing. Similarly, 30 μm sized TiC particle and B_4C are purchased from standard suppliers. The weight proportions of the metal powders of aluminium (Al), titanium carbide (TiC) and boron carbide (B_4C) are in 98 + 1.5 + 0.5 weight percentages, respectively. The mixture of metal powder proportions is maintained throughout the process and they are made to blend in a ball mill for a duration of 15 mins rotating at a speed of 300rpm. The powder compaction process is the next step to proceed with a punch

and die arrangements. The compaction die and punch are made of die steel materials. Specimens ejected from the die are in a cylindrical shape with a dimension of ϕ15 x 10 mm. Figure 1 shows the dimension of the photo image of green compaction of Al + TiC + B_4C powder along with the punch and die arrangements. For single-sample compaction, the amount of metal powder used is 40g. Hence, the uniformity of all the samples will be maintained the same in all the specimens for comparison and investigations. Compaction load for metal powder is given through heavy (10Ton) hydraulic press. In this work, the compaction force applied to specimen making is in terms of pressure and is varied in the range of 250–350MPa. Along with the sintering time, compaction pressure and sintering temperature are the allied parameters used in the proposed work. The levels of variation of these factors are given in Table 1.

Fig. 1.(a) Punch and die arrangement setup; (b) Al + TiC + B_4C composite specimen.

Table 1. Details of Al + TiC + B_4C powder compaction process parameters.

2.2 Taguchi method

Taguchi method is an appealing statistical technique to optimize process parameters in any setting, and it can also reduce the number of experiments involved. The experimental results were analyzed in the present work through an analysis of the Taguchi based S/N ratio. In general, three types of quality characteristics, such as smaller-the-better, higher-the-better, and nominal-the-better, can be used to evaluate the S/N ratio. This paper's primary objective is to identify the optimum levels of process parameters for developing composites with low density, high hardness, and high compression strength. Hence, the smaller-the-better quality characteristic was selected for density and higher-the-better quality characteristics were selected for hardness and compression strength. By ANOVA, the contribution made by each process parameter in affecting the material properties was determined. The performance of a group of input process parameters on the experimental data can also be identified using

ANOVA. Probable combinations of input parameter proposed for sample preparation are given in Table 2.

Table 2. Probable combination of process parameters composite development.

2.3 Testing and evaluation of composite material

A sequence of the procedure has been followed to prepare samples by green compaction and subsequently, sintering is done at a corresponding temperature for a defined duration. Minimum of four samples has been prepared in each combination for testing and evaluation. Once the sintering and curing are done, the samples are subjected to mechanical testing. Density, microhardness and compression strength investigations are done to evaluate the mechanical properties of the specimen. Density has been calculated based on the Archimedes principle using density meter (Model/Make: Mettler Toledo). The samples have been metallurgically polished to find the hardness at an applied load of 100g. A fresh sample is placed in a universal loading machine (Make/Model: UTM–FIE, UTN-40) to study the compression strength. The results are tabulated and mathematically evaluated to identify the best process parameter. Inferences are made for each sample with reference to the input process parameters. From the discussion, the best combination of process parameter has been identified and reported.

3. Results and Discussion

The aluminium (Al wt. 98%) matrix composite has been developed using the reinforcement particles titanium carbide and boron carbide (1.5% TiC + 0.5%B_4C). The composite has been processed at varying levels of process parameters. To study the metallurgical bonds of the composites, they have been evaluated using electron microscopy and energy dispersive spectroscopic analysis. Samples are metallurgically polished and the etchant has been applied to reveal the microstructure. Keller's is the etchant used for aluminium based material, which has been prepared with the combination of methanol,

hydrochloric acid, nitric acid (25 + 25 + 25ml) and 1 drop of hydrofluoric acid applied for 10–60 sec. The hard particle reinforced inside the matrix is clearly observed through an EVO18 Carl ZEISS electron microscope (as shown in Fig. 2). The structure reveals more even distribution of SiC reinforcement particles in between the soft aluminium matrix material. At higher magnification, the grain boundaries of the processed composite pressed at a pressure of 350 MPa, sintered at a temperature of 600°C for 2.25hr are revealed with a metallurgical bonding.–It is also evidently proved that the composite examined under the microscope has a pure bulk material by completely eliminating the voids and pores. Thus, the prepared sample will yield good surface hardness and bulk density.

Fig. 2. Electron imaging of Al + TiC + B_4C composite reflecting the reinforcement and grain boundaries.

Figure 3 shows the EDS result of the aluminium based MMC sample with the presence of alloying element through SEM and EDS mapping. The quantum spectra have proved the presence of Al, Ti, B and C (94 + 1 + 4 + 1 wt.%) in the composite used for examination. The SEM microscope shows the hard particle reinforced in the matrix material. The spectra imaging shows the color variation of each alloying elements present in the composite (both matrix and reinforcement) and they are visibly recorded. The results of the composite processed in the proposed design have revealed the same for all the conditions.

Fig. 3. Electron imaging and spectroscopic results of Al + TiC + B_4C after sintering.

3.1 Density of sintered (Al + TiC + B_4C) composite

The samples produced as per the sintering time, compaction pressure and sintering process mentioned in run order have been investigated to study the density, hardness and compressive strength of the Al + TiC + B_4C composite material. In each condition, a minimum of three samples has been considered for investigation. The first and foremost part

is the density of the sintered Al + TiC + B_4C composite material. Table 3 shows the value of the density of developed composite measured as per ASTM Standard. The density of the pure aluminium powder is 2.7g/cc. The result has revealed that there was a wide variation in the range of 2.58–2.89 g/cc in the average density of the Al + TiC + B_4C composite material processed at different conditions. The major difference in density is due to the compaction load applied. That is, the maximum average density of 2.89 g/cc is measured for the compaction load of 300MPa sintered at a 630°C for 2.25hr. Similarly, the minimum average density is 2.58 g/cc for a compaction load of 250MPa and sintered at 600°C at 1.75hr. In both the conditions, the value of all the parameters has a maximum difference. To make an inference on process parameter, the experimental results are mathematically evaluated and analyzed using S/N ratio and ANOVA.

Table 3. Density and S/N ratio values of Al + TiC + B_4C processed composite.

Table 4. Response table for density.

Fig. 4. Main effect plot for density.

Table 4 shows the S/N ratio table and means response table for the density. From the rank mentioned in the tables, it is clear that the density of the composite material is mostly influenced by the compaction pressure. In this work, the maximum compaction load applied will allow the metal powders to set compact within the defined volume on compression. On subsequent heat treatment of the green compact, the powder molecule starts to fuse and gets close to metallurgical bonding, during continuous sintering. Hence, the sintering temperature finds a second major contribution leaving sintering time at the least position. Figure 4 shows the effect of input process parameters on density. It shows that the low density has been achieved with a sintering time of 1.75hr at a sintering temperature of 600°C and maximum compaction pressure of 250MPa. Table 5 and Fig. 5 shows the results of ANOVA and the

contribution of each parameter on density. It is also confirmed that compaction pressure is considered for the most significant parameter with the contribution of 64.69% followed by sintering temperature 11.72%. Figure 6 shows the normal probability plot for density, which indicates the residuals are distributed along the straight line within 95% CI.

Table 5. ANOVA results for density.

Fig. 5. Influence of input parameters on density of Al + TiC + B_4C processed composite.

Fig. 6. Normal probability plot for density.

3.2 Microhardness of sintered (Al + TiC + B_4C) composite

The samples after density measurement are metallurgically polished and cleaned with ethanol for diamond indentation test in order to read the micro Vickers hardness of the sample. The ASTM standard procedure has been followed and three random spots have been identified for each sample. The average value of the first sample is denoted as hardness 1 and a similar procedure is followed to sample 2 and sample 3 for hardness 2 and hardness 3. The average of the hardness value measured is in the range of 23 – 29.78 Hv and is noted in Table 6. The average hardness of pure aluminium powder is 26Hv. Metallurgically, it is proved from the results obtained that, when the powder compaction is made with high density and less permeability, the surface hardness will be increased on proper heat treatment. The experimental trial 1 shows an average hardness of 23Hv, where the compaction pressure is 250MPa. At the same time, the powder compressed at 350MPa with a sintering temperature of 600°C at 2.25h has produced maximum surface hardness of 29.78 Hv. Table 7 illustrates the S/N ratio table and means response table for the hardness. From the table, it can be understood that the hardness of composite depends upon the compaction pressure and sintering time. Figure 7 shows the main effect plot that explains the influence and impact of

input process parameters on hardness. It displays that, the high hardness has been obtained with a sintering time of 2.25hr at a sintering temperature of 615°C and compaction pressure of 350MPa. Table 8 and Fig. 8 the ANOVA results and the influence and contribution of process parameters on hardness. From the graph, it is clear that compaction pressure is the most overriding parameter with the maximum contribution of 57.09% followed by sintering time 21.72%. Significantly, it has to be correlated that when the density of the material is good with less pores/voids, the bulk material properties will be enriched. On further heat treatment, the amount of time given to fuse the powder for metallurgical bonding will also show an impact on the surface hardness. Figure 9 shows the normal probability plot for hardness which indicates the residuals are distributed along the straight line within 95% CI.

Table 6. Hardness and S/N ratio value of Al + TiC + B_4C processed composite.

Table 7. Response table for hardness.

Fig. 7. Main effect plot for hardness.

Table 8. ANOVA results for hardness.

Fig. 8. Influence of input parameters on hardness of Al + TiC + B_4C composite.

Fig. 9. Normal probability plot for hardness.

3.3 Compression strength of Al + TiC + B_4C metal matrix composite

A set of samples has been subjected to a negative axial loading condition to study the compression strength of the fabricated Al + TiC + B_4C specimens. The photo images of the sample before and after the compression test (as per ASTM Standards) are given in Fig. 10. If the sample for experimental trial 1 is processed at 250MPa compression pressure with 600°C sintering temperature for 1.75h, the maximum load sustained for the failure is 55.77kN with an ultimate strength of 313.94MPa compression strength as shown in Fig.10. The material gets in ductile failure with upsetting. The shape of the compressed sample becomes a

complete circle than the oval in shape with brittle or buckling at the end. The surface of the compressed sample is found with a good finish and it has produced a good friction coefficient for uniform distribution while compression. Edges are failed and opened, due to the surface tensile loading with a minimum of bandgap in the form of microcracks. The compression strength of the Al + TiC + B_4C composite material is presented in Table 9. With the experimental values obtained through the proposed design, the S/N ratio has been evaluated and reported to study the process parameter. Table 10 shows the S/N ratio table and the response of means table for compression strength. It is observed that sintering time contributes maximum than sintering temperature and the compaction pressure. The results indicate that with extended sintering time if the metal powders are properly diffused to have a metallurgical bonding, the strength of the material can be increased.

Fig. 10. Photo image of Al + TiC + B_4C composite before and after compression.

Table 9. Compression strength and S/N ratio value of Al + TiC + B_4C processed composite.

Table 10. Response table for compression strength.

Figure 11 shows the main effect plot for compressive strength that illustrates the effect of PM process parameters on compressive strength. It illustrates that the maximum compression strength was attained by a sintering time of 1.75hr at a sintering temperature of 600°C and compaction pressure of 250MPa. Table 11 and Fig.12 explain the ANOVA results and the effect that each parameter offers on compression strength. The sintering time was identified to be the most significant parameter on the compression strength with the contribution of 56.22% followed by sintering temperature of 26.98%. The distribution of residuals along the straight line with 95% CI was confirmed from the normal probability plot depicted in Fig. 13.

Fig. 11. Main effect plot for compression strength.

Table 11. ANOVA results for compression strength.

Fig. 12. Influence of input parameters on compression strength of Al + TiC + B_4C composite.

Fig.13. Compression strength in normal probability plot.

3.4 Combined effects of the parameters on density, hardness and compression strength

The interaction plot can be used to indicate that, how the combined effect of the process parameters affects the output response. From the plot, the presence of the interaction effect can be known by the presence of non-parallel lines and vice-versa. Figures 14, 15 and 16 show the interaction plot for density, hardness and compression strength. The interaction plot is shown in Fig.15 clearly depicts that composites hardness increases with compaction pressure. At elevated compaction pressure values, higher values of hardness is noted. The increase in hardness by high compaction pressure is due to the reduction in porosity content and perfect packing of reinforcements in between the matrix. The interaction effect produced by sintering temperature and compaction pressure is significant at lower sintering temperature and insignificant at higher temperatures. Also, the interaction effect produced by sintering time and compaction pressure is significant at higher sintering time, and insignificant at the lower sintering time.

Fig. 14. Interaction plot for density.

Fig. 15. Interaction plot for hardness.

Fig. 16. Interaction plot for compression strength.

3.5 Optimized parameters

Table 12 shows the optimum level of process parameters to attain low density, high hardness and compression strength of Al + TiC + B_4C composite material.

Table 12. Optimized parameters.

4. Conclusions

The composite material has been developed by reinforcing the TiC and B_4C in the aluminium matrix through PM route. The properties of the composite material have been evaluated by varying the input process parameters. The influence of individual input parameters has been analyzed using the Taguchi method. Following are the significant points to conclude with the proposed research:

1. The low density of composite attained by the optimum level parameters are sintering time of 2hr, sintering temperature at 615°C and compaction pressure of 250MPa. It has been confirmed that the compaction pressure is the most impact parameter with a contribution of 71.53% when compared with sintering temperature and sintering time.
2. The high hardness of the composite material has been found with the optimum parameter setting of sintering time at 2.25hr, sintering temperature at 615°C and compaction pressure of 350MPa. The compaction pressure is the highly influencing parameter on hardness followed by sintering time.
3. By following sintering time of 1.75hr, sintering temperature at 600°C and compaction pressure of 250MPa, the maximum compressive strength can be achieved. Sintering time and sintering temperature mostly affect compression strength. Based on the sintering condition, the metallurgical quality of the composite is enriched.

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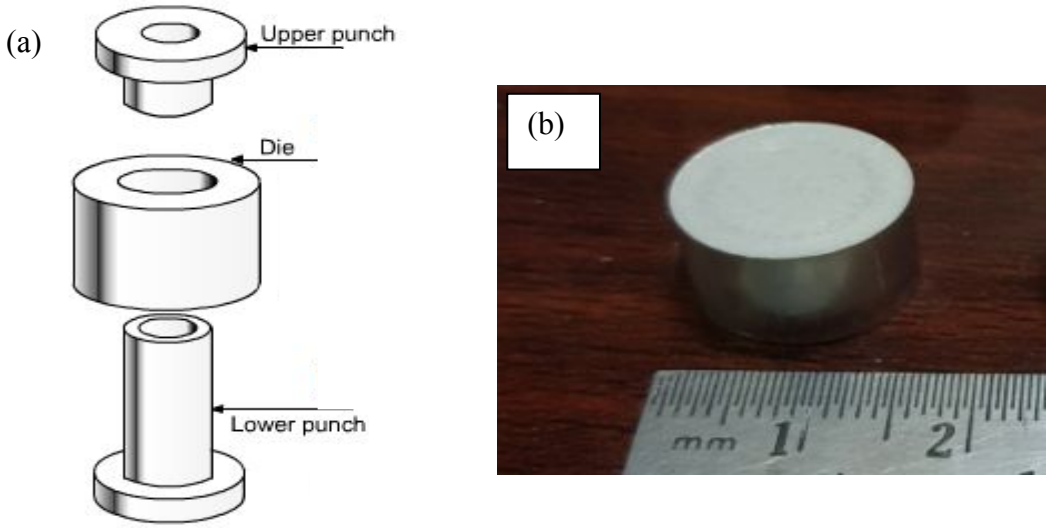

Fig. 1.(a) Punch and die arrangement setup; (b) Al + TiC + B_4C composite specimen.

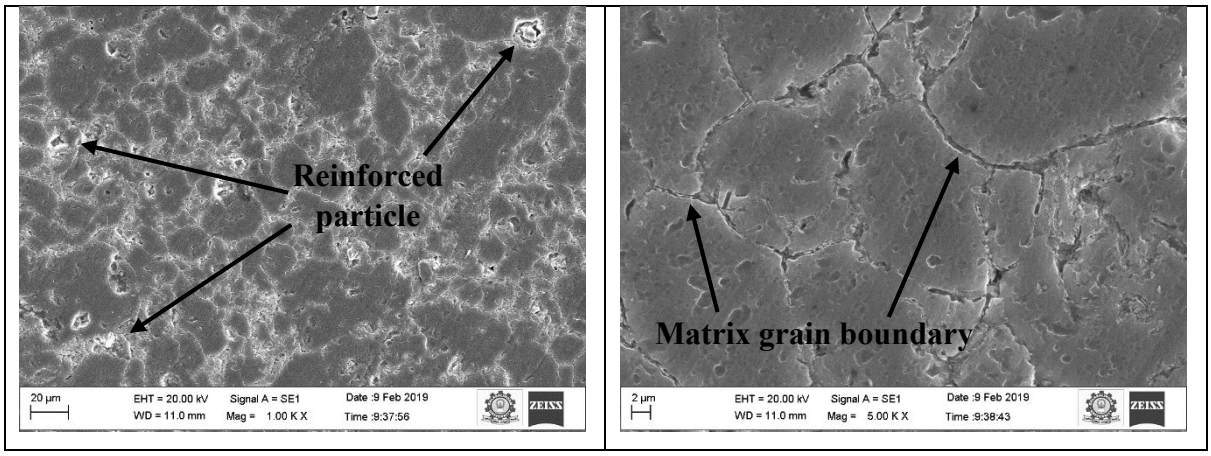

Fig. 2. Electron imaging of Al + TiC + B_4C composite reflecting the reinforcement and grain boundaries.

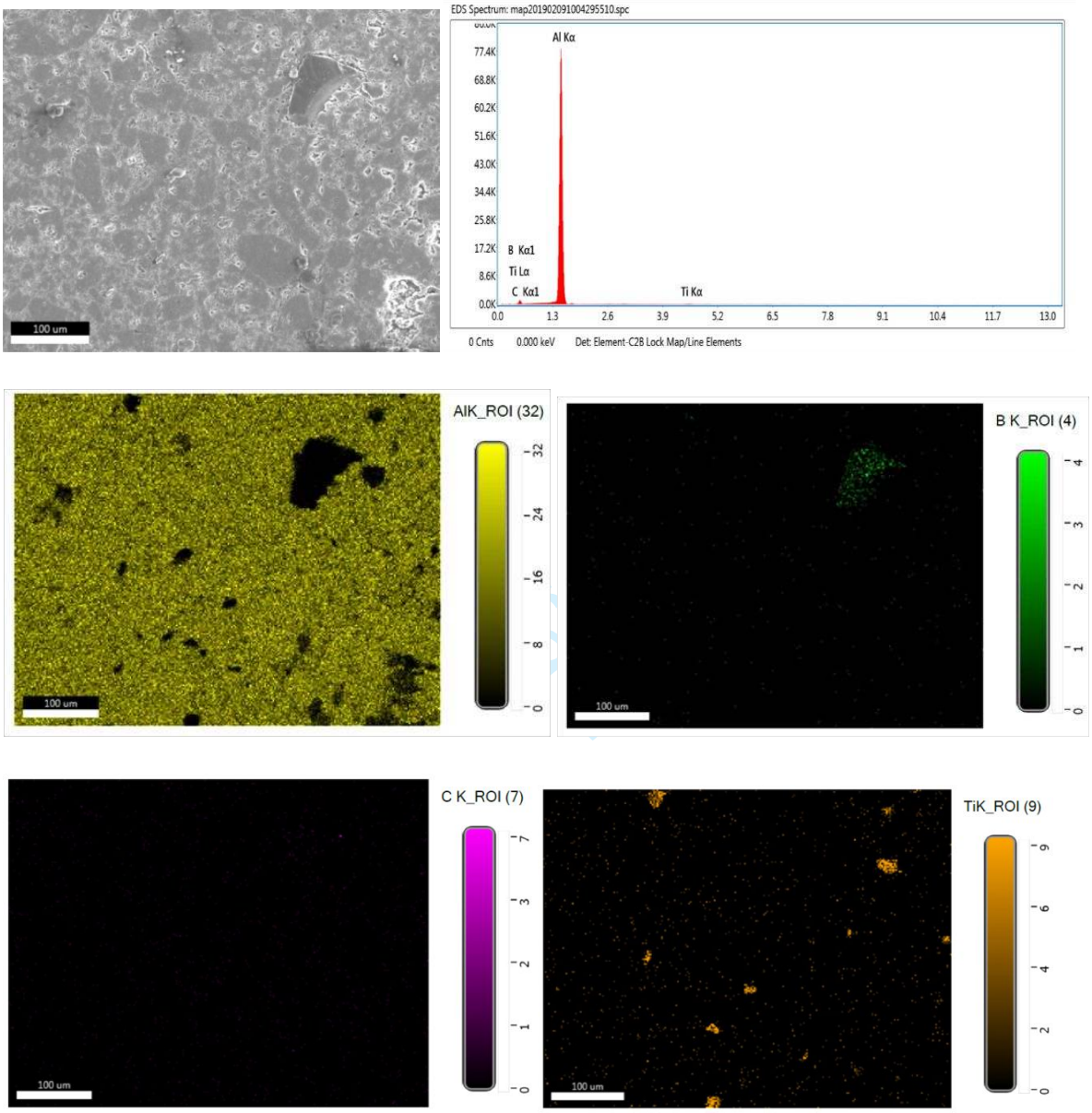

Fig. 3. Electron imaging and spectroscopic results of Al + TiC + B_4C after sintering.

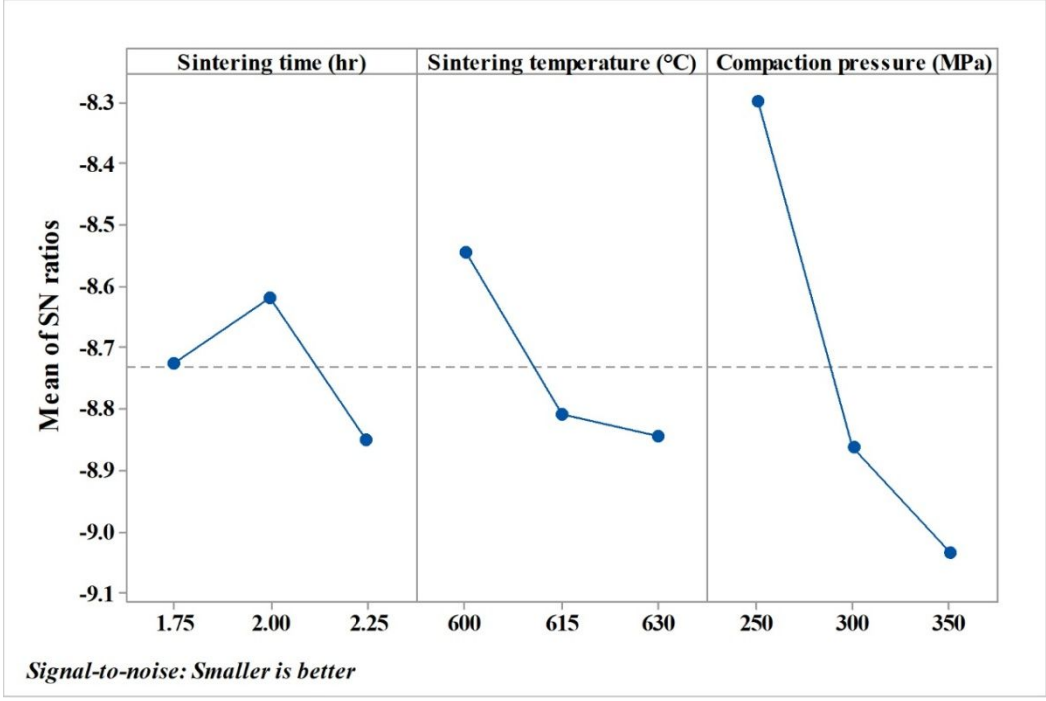

Fig. 4. Main effect plot for density.

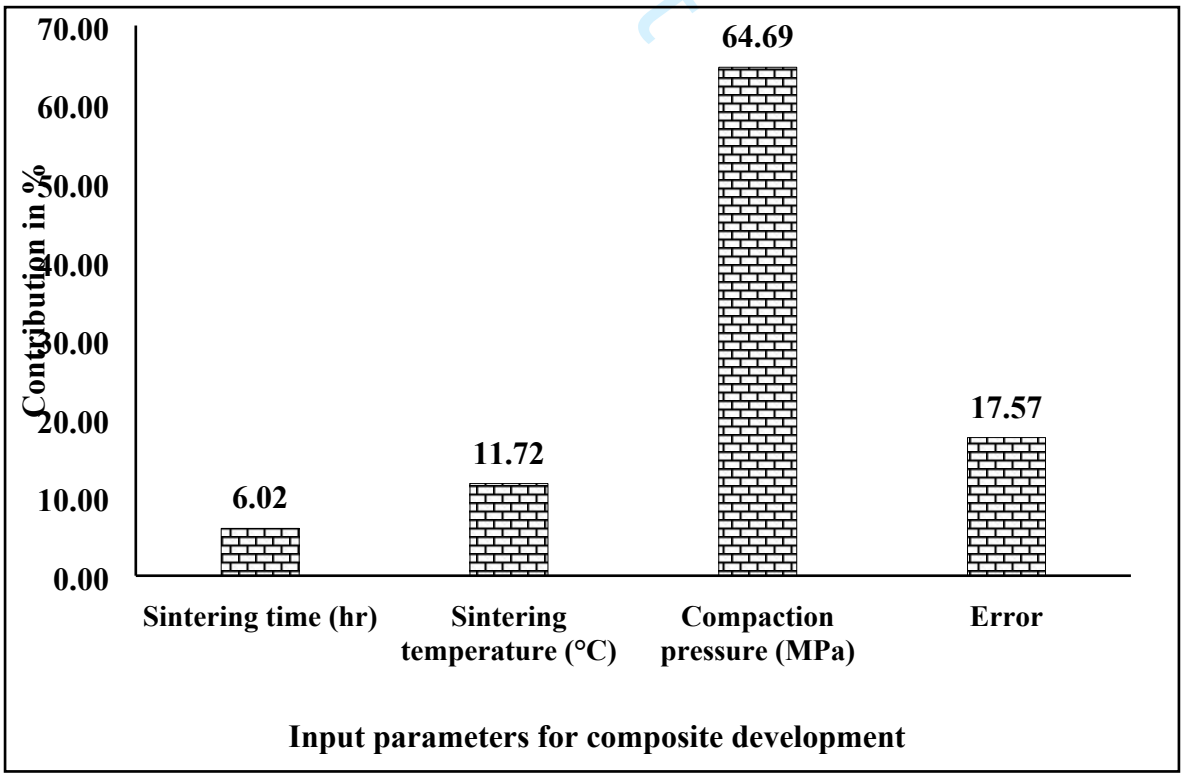

Fig. 5. Influence of input parameters on density of Al + TiC + B_4C processed composite.

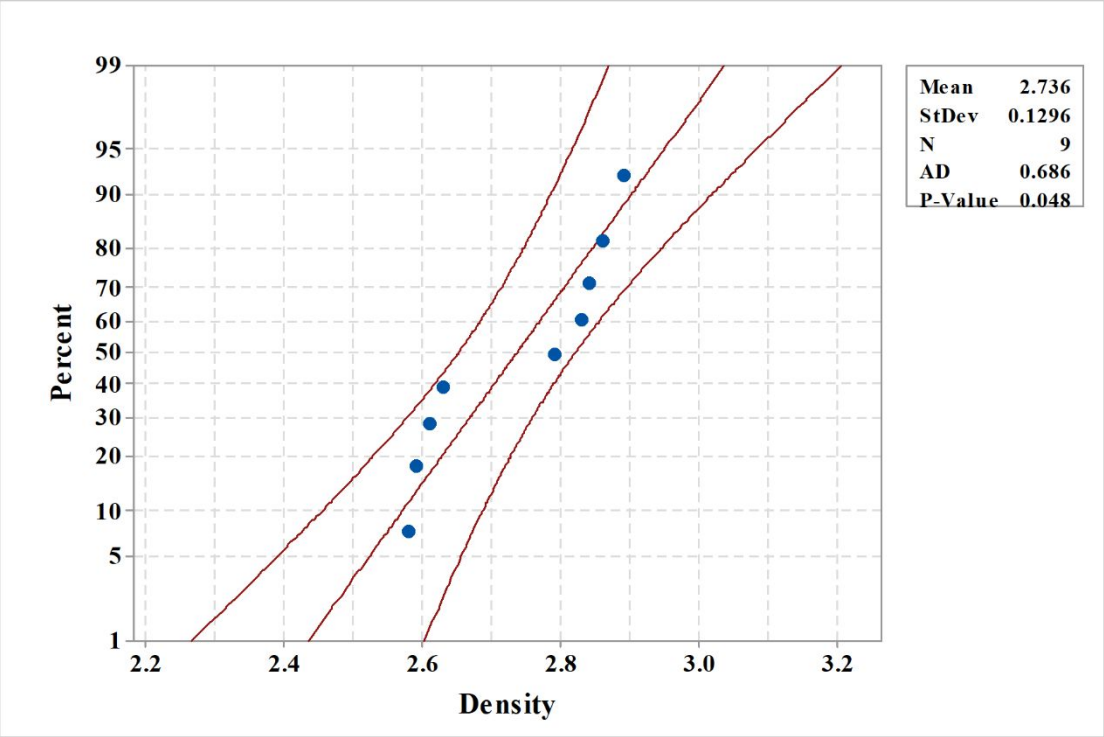

Fig. 6. Normal probability plot for density.

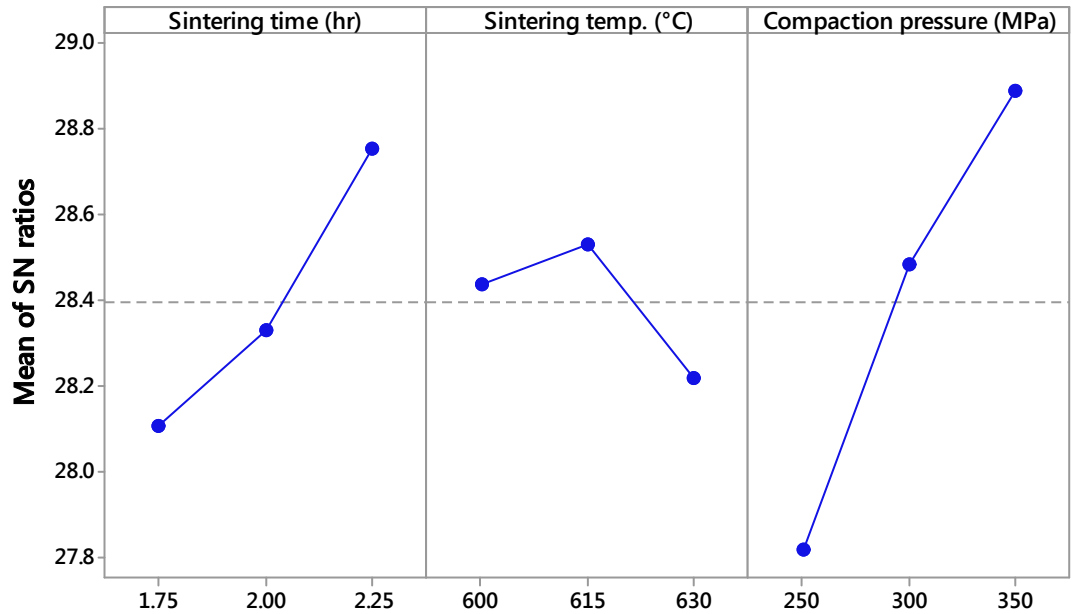

Fig. 7. Main effect plot for hardness.

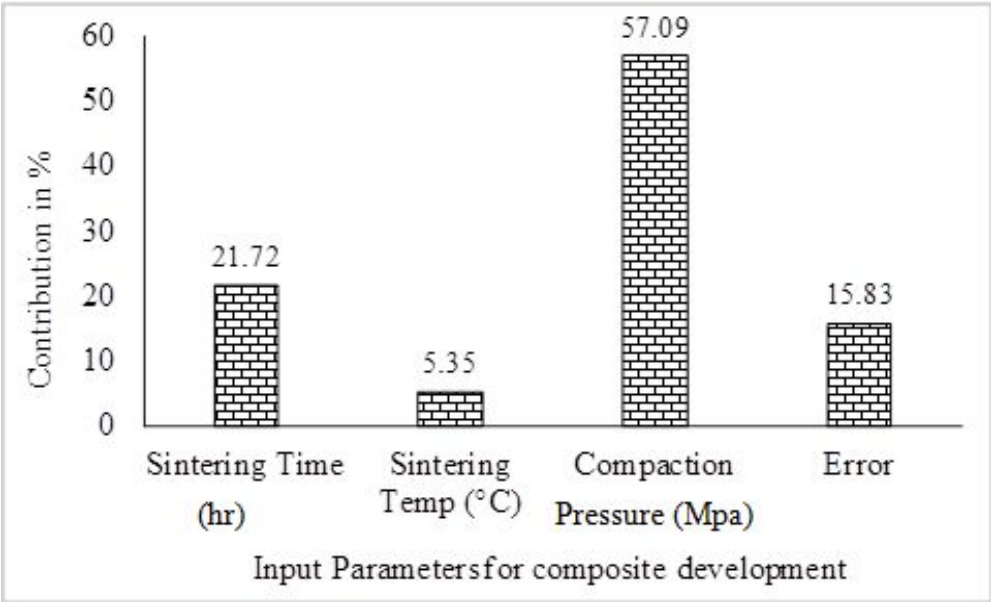

Fig. 8. Influence of input parameters on hardness of Al + TiC + B_4C composite.

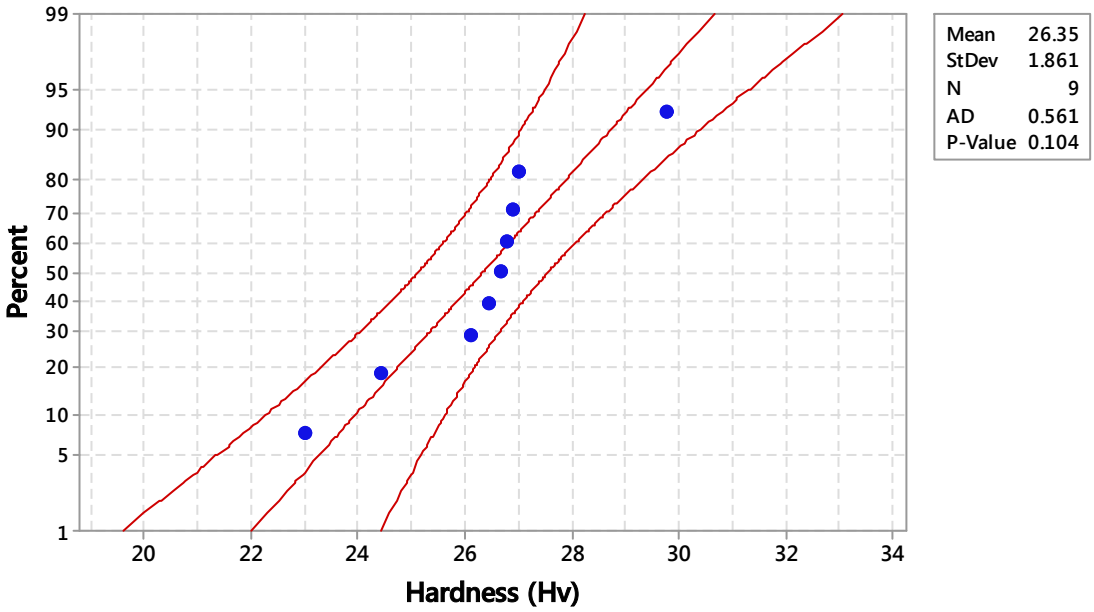

Fig. 9. Normal probability plot for hardness.

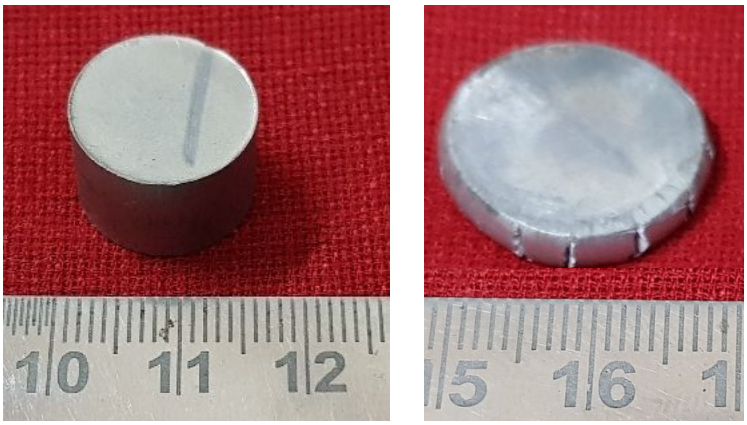

Fig. 10. Photo image of Al + TiC + B_4C composite before and after compression.

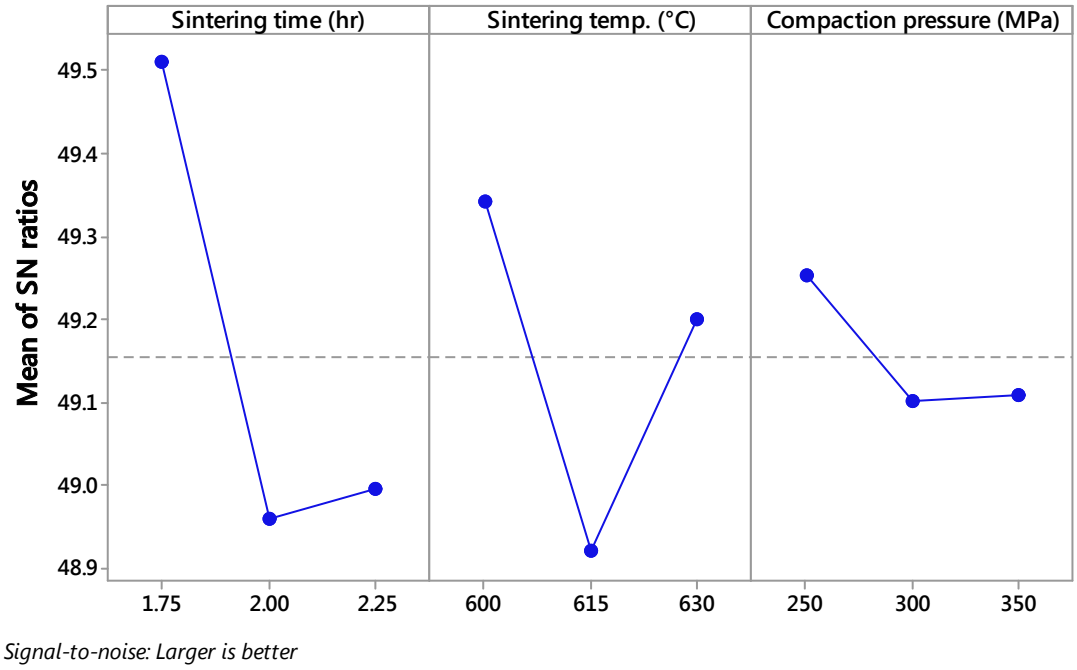

Fig. 11. Main effect plot for compression strength.

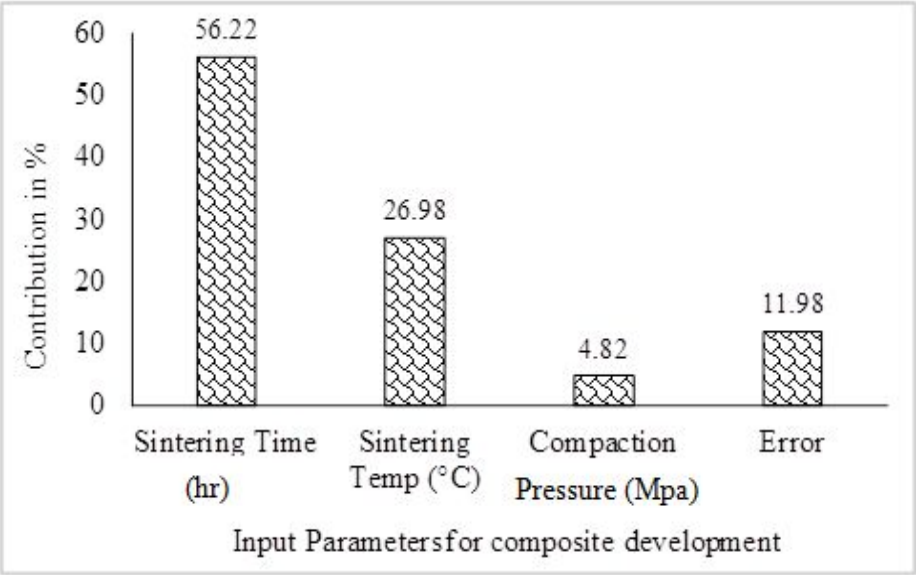

Fig. 12. Influence of input parameters on compression strength of Al + TiC + B_4C composite.

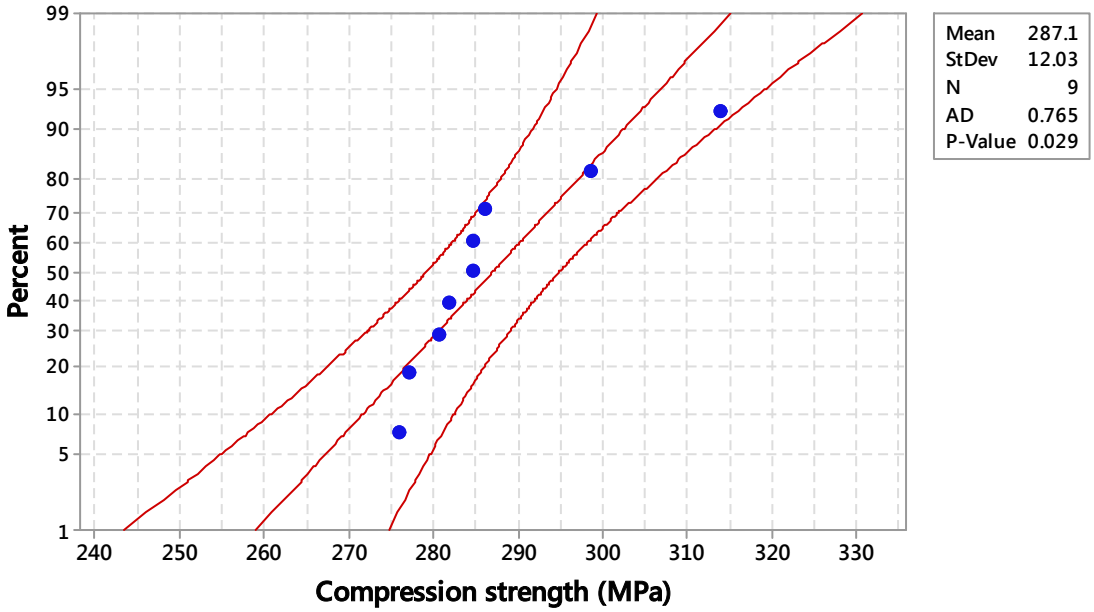

Fig.13. Compression strength in normal probability plot.

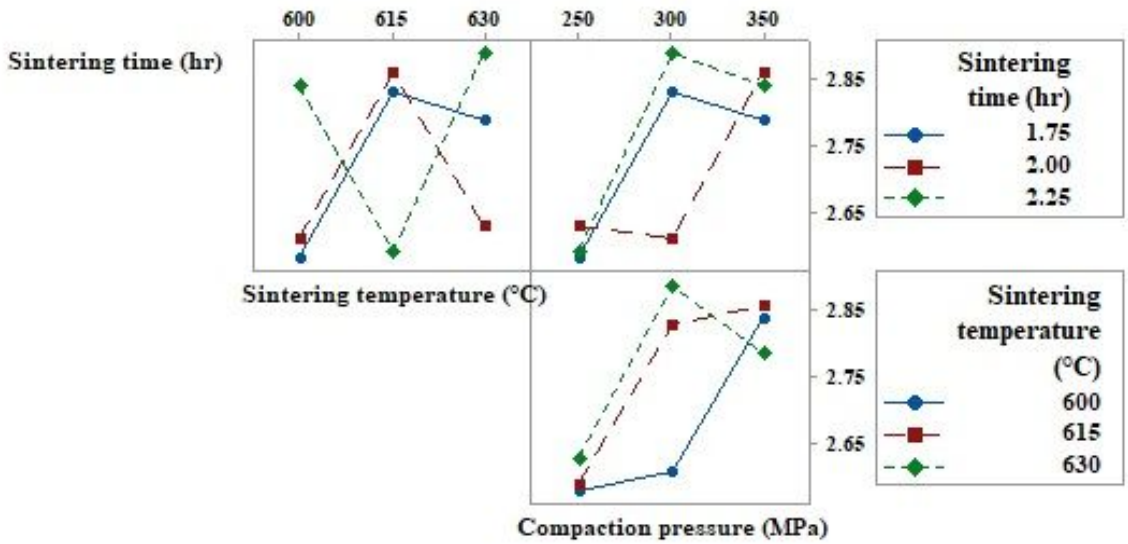

Fig. 14. Interaction plot for density.

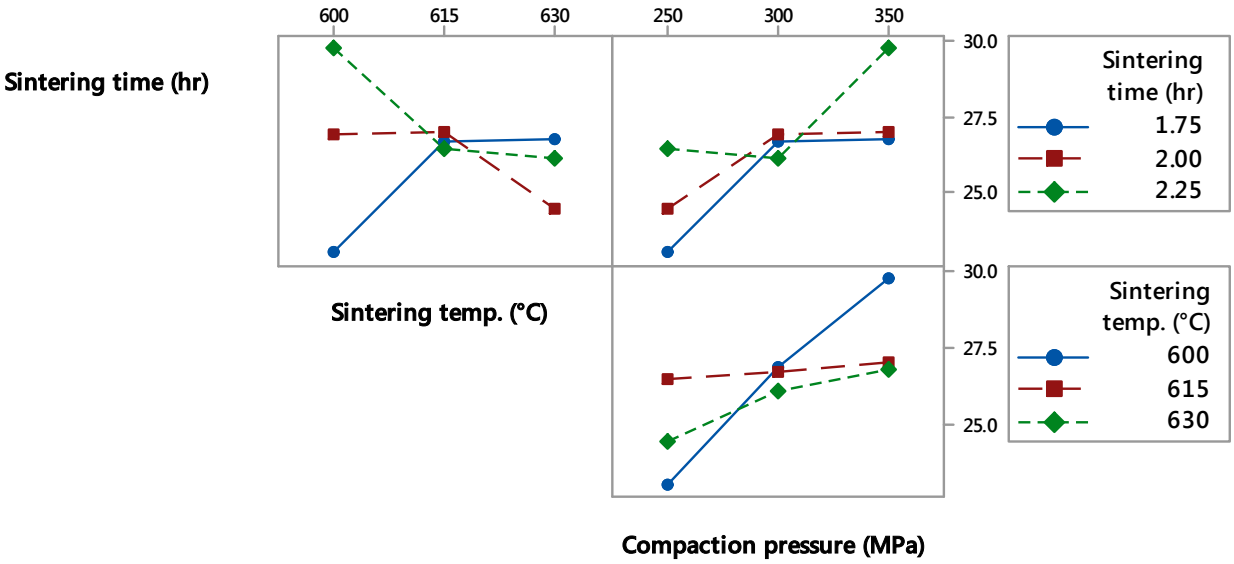

Fig. 15. Interaction plot for hardness.

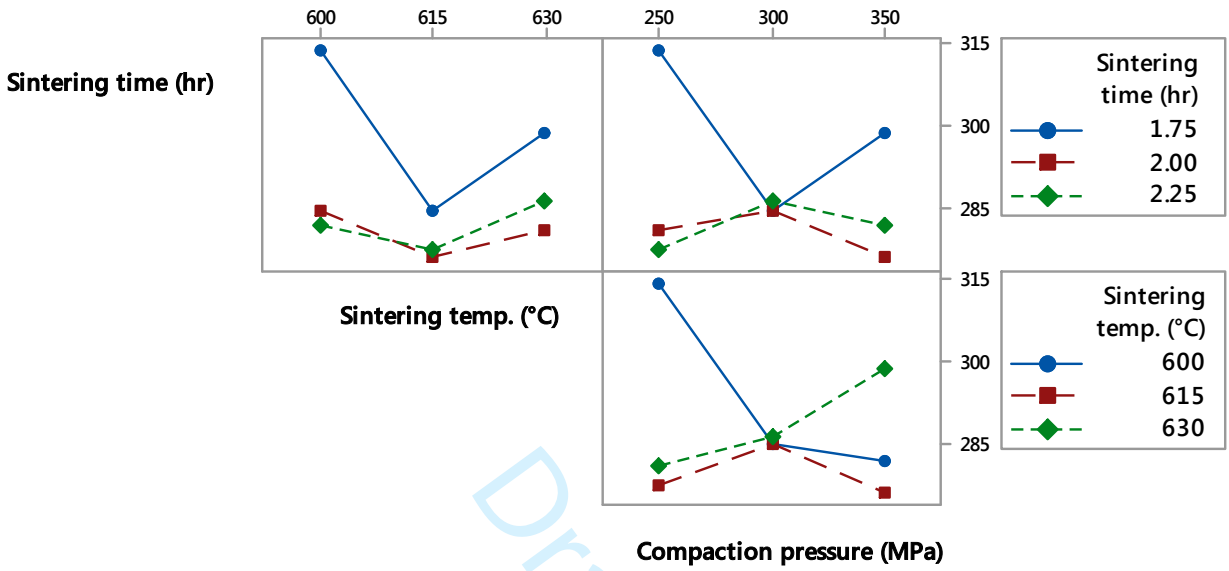

Fig. 16. Interaction plot for compression strength.

Table 1. Details of Al + TiC + B_4C powder compaction process parameters.

Process parameter	Range	Units
Sintering time	1.75, 2 and 2.25	hr
Sintering temperature	600, 615 and 630	°C
Compacting pressure	250, 300 and 350	MPa

Table 2. Probable combination of process parameters composite development.

Exp no.	Sintering time (hr)	Sintering temperature (°C)	Compaction pressure (MPa)
1	1.75	600	250
2	1.75	615	300
3	1.75	630	350
4	2	600	300
5	2	615	350
6	2	630	250
7	2.25	600	350
8	2.25	615	250
9	2.25	630	300

Table 3. Density and S/N ratio values of Al + TiC + B_4C processed composite.

Exp No.	Sintering time (hr)	Sintering temp. (°C)	Compaction pressure (MPa)	Density (g/cc)	S/N ratio
1	1.75	600	250	2.58	-8.2324
2	1.75	615	300	2.83	-9.0357
3	1.75	630	350	2.79	-8.9121
4	2	600	300	2.61	-8.3328
5	2	615	350	2.86	-9.1273
6	2	630	250	2.63	-8.3991
7	2.25	600	350	2.84	-9.0664
8	2.25	615	250	2.59	-8.2660
9	2.25	630	300	2.89	-9.2180

Table 4. Response table for density.

S/N ratio of density			
Level	Sintering time (hr)	Sintering temp (°C)	Compaction pressure (MPa)
1	-8.727	-8.544	-8.299
2	-8.620	-8.810	-8.862
3	-8.850	-8.843	-9.035
Delta	0.230	0.299	0.736
Rank	3	2	1
Means of density			
1	2.733	2.677	2.600
2	2.700	2.760	2.777
3	2.773	2.770	2.830
Delta	0.073	0.093	0.230
Rank	3	2	1

Table 5. ANOVA results for density.

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Sintering time (hr)	2	0.008089	0.008089	0.004044	0.34	0.745
Sintering temperature (°C)	2	0.015756	0.015756	0.007878	0.67	0.600
Compaction pressure (MPa)	2	0.086956	0.086956	0.043478	3.68	0.214
Error	2	0.023622	0.023622	0.011811		
Total	8	0.134422				

Table 6. Hardness and S/N ratio value of Al + TiC + B_4C processed composite.

Exp no.	Sintering time (hr)	Sintering temp. (°C)	Compaction pressure (MPa)	Hardness (Hv)	S/N ratio (dB)
1	1.75	600	250	23.00	27.235
2	1.75	615	300	26.67	28.520
3	1.75	630	350	26.78	28.556
4	2	600	300	26.89	28.592
5	2	615	350	27.00	28.627
6	2	630	250	24.44	27.762
7	2.25	600	350	29.78	29.478
8	2.25	615	250	26.44	28.445
9	2.25	630	300	26.11	28.336

Table 7. Response table for hardness.

S/N ratio of hardness			
Level	Sintering time (hr)	Sintering temp (°C)	Compaction pressure (MPa)
1	28.10	28.43	27.81
2	28.33	28.53	28.48
3	28.75	28.22	28.89
Delta	0.65	0.31	1.07
Rank	2	3	1
Means of hardness			
1	25.48	26.56	24.63
2	26.11	26.70	26.56
3	27.44	25.78	27.85
Delta	1.96	0.93	3.23
Rank	2	3	1

Table 8. ANOVA results for hardness.

Source	DF	Seq SS	Adj SS	Adj MS	F-value	P-value
Sintering time (hr)	2	6.012	6.012	3.006	1.37	0.422
Sintering temp (°C)	2	1.489	1.489	0.744	0.34	0.747
Compacting pressure (MPa)	2	15.818	15.818	7.909	3.16	0.217
Error	2	4.384	4.384	2.192		
Total	8	27.702				

Table 9. Compression strength and S/N ratio value of Al + TiC + B_4C processed composite.

Exp no.	Sintering time (hr)	Sintering temp. (°C)	Compaction pressure (MPa)	Compression strength (MPa)	S/N ratio (dB)
1	1.75	600	250	313.94	49.937
2	1.75	615	300	284.64	49.086
3	1.75	630	350	298.74	49.506
4	2	600	300	284.69	49.087
5	2	615	350	276.05	48.820
6	2	630	250	280.77	48.967
7	2.25	600	350	281.84	49.000
8	2.25	615	250	277.13	48.854
9	2.25	630	300	286.08	49.130

Table 10. Response table for compression strength.

S/N ratio of compression strength			
Level	Sintering time (hr)	Sintering temp (°C)	Compaction pressure (MPa)
1	49.51	49.34	49.25
2	48.96	48.92	49.10
3	48.99	49.20	49.11
Delta	0.55	0.42	0.15
Rank	1	2	3
Means of compression strength			
1	299.1	293.5	290.6
2	280.5	279.3	285.1
3	281.7	288.5	285.5
Delta	18.6	14.2	5.5
Rank	1	2	3

Table 11. ANOVA results for compression strength.

Source	DF	Seq SS	Adj SS	Adj MS	F-value	P-value
Sintering time (hr)	2	651.05	651.05	325.52	4.69	0.176
Sintering temp (°C)	2	312.40	312.40	156.20	2.25	0.307
Compacting pressure (MPa)	2	55.86	55.86	27.93	0.40	0.713
Error	2	138.70	138.70	69.35		
Total	8	1158.02				

Table 12. Optimized parameters.

Output response	Optimum parameter level		
	Sintering time (hr)	Sintering temp. (°C)	Compacting pressure (MPa)
Density (g/cc)	2	615	250
Hardness (Hv)	2.25	615	350
Compression strength (MPa)	1.75	600	250