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OPTIMIZATION OF THE DRILLING PARAMETERS FOR THE CUTTING FORCES IN B_4C-REINFORCED Al-7XXX-SERIES ALLOYS BASED ON THE TAGUCHI METHOD

OPTIMIRANJE PARAMETROV VRTANJA ZA SILE VRTANJA PRI ZLITINAH Al-7XXX, OJAČANIH Z B_4C S TAGUCHIJEVO METODO

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In this study, drilling tests of aluminum-based composites produced with the powder-metallurgy (PM) technique and reinforced with boron-carbide (B_4C) particles were carried out with three different types of drills under dry cutting conditions. In order to determine the mechanical properties of the produced composites, hardness and tensile tests were performed. Moreover, the effects of the machining parameters such as cutting speed, feed rate, particle fraction and cutting-tool material, and of their interactions on the thrust force and cutting torque were determined with the Taguchi experimental design. Drilling parameters were optimized in terms of cutting forces (thrust force and torque). Furthermore, an analysis of variance (ANOVA) was conducted to obtain the degree of the effect of the parameters. The most influential control factors for the cutting forces were found to be the particle fraction and feed rate. According to the experimental results, the thrust force and cutting torque increased significantly as the feed rate or the particle content increased. On the other hand, the influence of the drill-bit material and the interactions of the factors for the cutting forces were quite low.

Keywords: B_4C, powder metallurgy, drilling, cutting force, torque, Taguchi method

V tej študiji so bili narejeni preizkusi vrtanja kompozita na osnovi aluminija, ojačanega z borovim karbidom (B_4C) in izdelanega po postopku prašne metalurgije (PM), s tremi različnimi svedri in pri suhem vrtanju. Za določitev mehanskih lastnosti izdelanega kompozita je bila izmerjena trdota in opravljeni so bili natezni preizkusi. Poleg tega so bili določeni s Taguchijevo eksperimentalno tehniko parametri obdelave, kot so hitrost rezanja, hitrost podajanja, delež delcev, material za orodje za rezanje in njihov vpliv na potisno silo ter navor pri rezanju. Parametri rezanja so bili optimirani glede na sile rezanja (potisna sila in navor). Poleg tega je bila narejena analiza variance (ANOVA), da bi dobili stopnjo vpliva parametrov. Ugotovljeno je bilo, da sta najbolj vplivna kontrolna faktorja na sile rezanja delež delcev in hitrost podajanja. Skladno z rezultati preizkusov potisna sila in navor močno narasteta, če se poveča hitrost podajanja ali poveča vsebnost delcev. Po drugi strani so razmeroma majhni vplivi materiala svedra in medsebojni vpliv faktorjev na sile rezanja.

Ključne besede: B_4C, prašna metalurgija, vrtanje, sila rezanja, navor, Taguchijeva metoda

1 INTRODUCTION

The composition of many composite materials used in engineering applications consists of additives providing a better hardness and resistance and of the matrix material that holds these substances together as well as allowing ductility and toughness.[1] Due to their high specific strength, superior wear resistance, low thermal expansion and lightweight, metal-matrix composites (MMCs), widely used, especially in aerospace and automotive industry, have attracted the attention of the researchers.[2–4] However, in spite of these advantages, the machinability of these composites is difficult.[5–12]

A drilling process is one of the last production stages that have to be done before the assembly step. The past studies relating to the drilling of MMCs have revealed that Al_2O_3 and SiC are mostly used as a reinforcement material in an aluminum composite material.[3,5–8,12–14] However, there are no adequate studies on the drilling of the B_4C-reinforced aluminum composites. An inclusion of the B_4C particles as a reinforcement material has the advantage of having a higher hardness (≈4200 HV) than the other ceramics such as SiC (≈3500 HV) and Al_2O_3 (≈2300 HV).[2,15]

In the previous studies regarding the drilling machinability of MMCs, it is stated that an increase in the cutting speed does not significantly affect the thrust force, and that the most important factor increasing the thrust force is the feed rate.[3,10,16] Moreover, the particle content in the composite material as well as the drilling tool are of importance for the drilling of aluminum-matrix composites; and the lowest drilling forces are obtained with polycrystalline diamond (PCD) drills.[3] In addition, the coated carbide tools produce more thrust forces than the uncoated carbide drills.[16] Heat-treatment conditions also have a significant effect on the cutting forces and the highest tool forces were observed (nearly twice) when drilling aged the composites.[6,8] On the other hand, while an addition of graphite to a composite material positively affects both the cutting forces and the machinability, it adversely affects the strength of the composite material.[2,5,12] With respect to the cutting-tool material, lower thrust forces are obtained when through-tool cooling is performed.[7] However, the cutting torques produced with conventional cooling (the cooling method, in which the cooling fluid is sprayed from the outside to the cutting zone) are lower than those produced with the through-tool cooling and dry drilling. Thrust forces also increase depending on the drilled hole number.[7] From the point of view of the cutting forces, the results of drilling fiber-reinforced composites are similar to the results of drilling MMCs.[9,11]

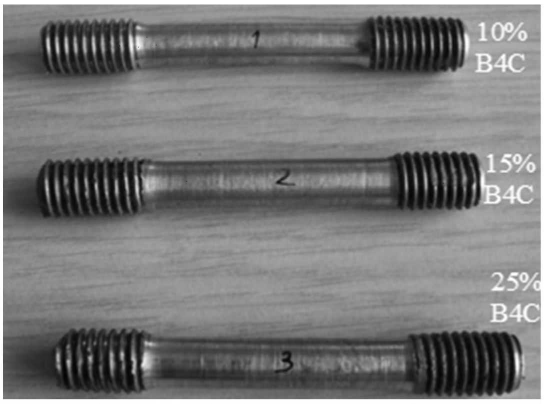
The Taguchi design method is a useful tool for determining the effect of machining parameters and their significance levels. A plan of experiments can be conducted with the Taguchi method with the purpose of analyzing the data and obtaining the information about the property of a certain process. This method uses orthogonal arrays for defining the experiment plan.[4,13,14,16] Its important advantage is the fact that it saves experimental effort and time, reducing the cost. Furthermore, the results other than the conducted experiments can be predicted with a great accuracy by using this method. In recent times, a variety of applications of the Taguchi method have been performed in many areas.

The aim of this study was to introduce the Taguchi method in determining the optimum drilling conditions for the thrust force and drilling torque when drilling an Al7XXX alloy reinforced with three different mass fractions of B_4C particles. For this purpose, the effect of the control factors such as spindle speed, feed rate, particle fraction and cutting tool on the cutting forces were investigated. Significance levels of individual factors were determined with ANOVA. The values predicted with the Taguchi method were compared with the experimental results.

2 EXPERIMENTAL PROCESS

2.1 Production of Composite Materials

In this work, 7xxx-series aluminum alloy (including mass fractions: 5 % zinc, 3.5 % copper and 2.5 % of magnesium) was used as the matrix element. B_4C ceramic powders under 325 meshes were used as the reinforcement element. To investigate the effects of different reinforcement fractions on the machinability, three different weight fractions of B_4C particles were selected as 10 %, 15 % and 25 %. The mixture was cold pressed in the mold under the pressure of 25 MPa in an electrical furnace. Then the internal temperature of the furnace was fixed at 540 °C and the composite materials were produced by applying the liquid-phase sintering method for half an hour. Later the produced samples were subjected to the hardness, tensile and drilling tests. For the hardness test, three hardness measurements were performed on each sample by using OKO SEIKI hardness-measurement equipment and the mean of the hardness values was used. Tensile tests were also carried out by placing each specimen into a 60-ton Tinius Olsen tensile-test device. Tensile-test specimens were prepared according to the EN 10002-1 standard by turning the sintered blocks as shown in **Figure 1**.



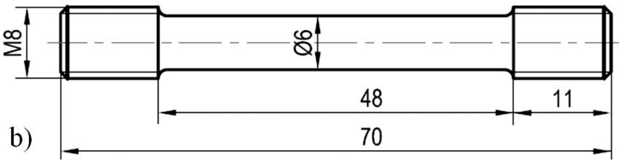


Figure 1: Tensile-test specimens: a) prepared test specimens, b) technical drawing of a test specimen

Slika 1: Preizkušanci za natezni preizkus: a) pripravljeni preizkušanci, b) tehnična risba preizkušanca

2.2 Test Setup and the Drilling Process

For the drilling tests of the produced MMCs, a computer numerically controlled (CNC) vertical machining center (VMC-550 Johnford Fanuc Series O-M) having the capacity of 15 kW and 3 500 r/min was used. The machining conditions and geometrical properties of the drills are given in **Table 1**. The cutting forces were measured for all the drilling experiments with three previously unused, different, 8-mm drills. Each test was repeated twice and the mean values were used. A total of 100 holes were drilled in addition to 27 Taguchi experiments for confirmation purpose. The length of the drilled composites was 12 mm. A KISTLER 9272 dynamometer was used to measure the thrust force and torque during the drilling process. **Figure 2** shows the schematic image of the drilling setup[17]. A picture of the produced composite, attached to a specially developed and manufactured fixture, after being drilled with the CNC vertical machining center, is depicted in **Figure 3**. After measuring the thrust forces and drilling torques, the results were recorded into a computer environment using the KISTLER DynoWare software. The average value of the measured cutting forces was taken into account so that the conical section of the tool tip was completely inside the workpiece. A sample output of the

Table 1: Machining conditions
Tabela 1: Pogoji obdelave

Machine tool	Johnford VMC-550 Fanuc Serial O-M CNC controlled vertical machining center	
Drills	HSS:	Φ 8 mm, 135° tool tip angle, spiral, 30° helical angle
	Uncoated carbide:	Φ 8 mm, 140° tool tip angle, spiral, 30° helical angle
	TiAlN-coated carbide:	Φ 8 mm, 140° tool tip angle, spiral, 30° helical angle
Workpiece materials	Mass fractions: 10 % B_4C/Al, 15 % B_4C/Al and 25 % B_4C/Al composite	
Cutting parameters	Spindle speeds (*n*): 1000 r/min, 1500 r/min, 2000 r/min, 2500 r/min Feed rates (*f*) : 0.1 mm/r, 0.2 mm/r, 0.3 mm/r	

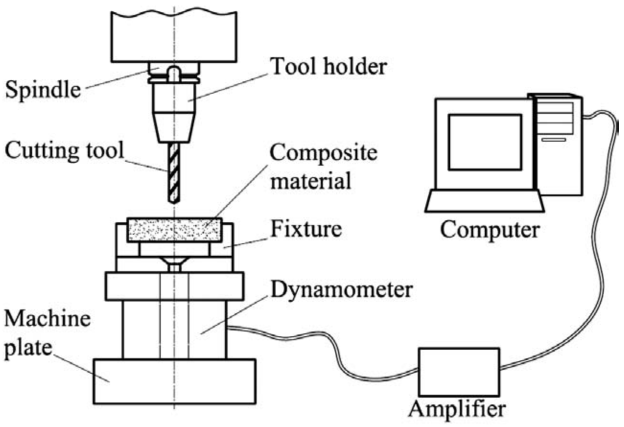


Figure 2: Schematic presentation of the measuring setup
Slika 2: Shematski prikaz sestava za merjenje

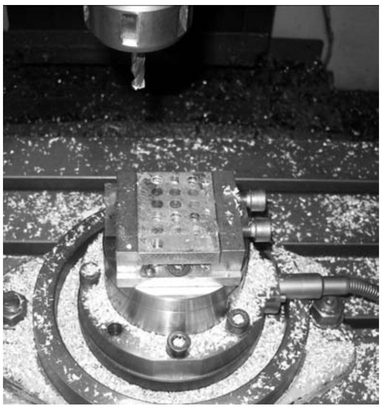


Figure 3: Drilling setup
Slika 3: Preizkus vrtanja

dynamometer showing the variation of the cutting force and torque is given in **Figure 4**.

3 RESULTS AND DISCUSSION

3.1 Microstructure and Mechanical Properties

The microstructure of the produced composites is shown in **Figure 5**. A homogeneous distribution of the ceramic particles over the composite alloy can be seen from this figure. According to the hardness test results, the average hardnesses of the specimens with mass fractions 10 % B_4C, 15 % B_4C and 25 % B_4C were meas-

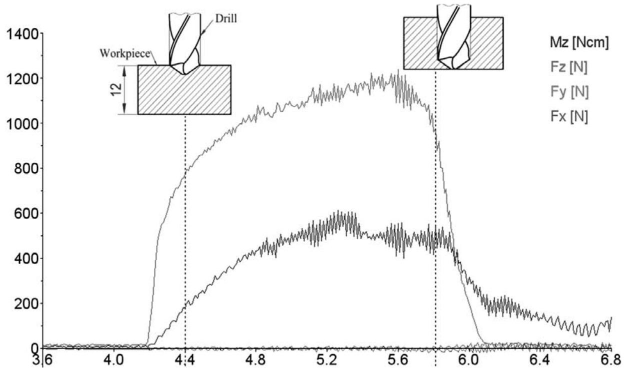


Figure 4: Typical cutting forces observed when spindle speed = 1500 r/min, feed = 0.3 mm/r, the work piece contains the mass fraction 10 % B_4C and the drill used is made of HSS
Slika 4: Značilna sila rezanja pri hitrosti vrtenja vretena = 1500 r/min, podajanje 0,3 mm/r, obdelovanec je vseboval masni delež 10 % B_4C, sveder je bil iz HSS-jekla

ured as 61 HRB, 79 HRB and 87 HRB, respectively. These hardnesses were significantly higher than that for the Al7075 alloy (43 HRB) but close to the Al7075–T6 alloy (87 HRB).[18] The hardness of the composites increased as the particle fraction increased due to the hard nature of the ceramic particles.

The results of the strength and elongation (%) for each sample are given in **Table 2**. The highest yield and

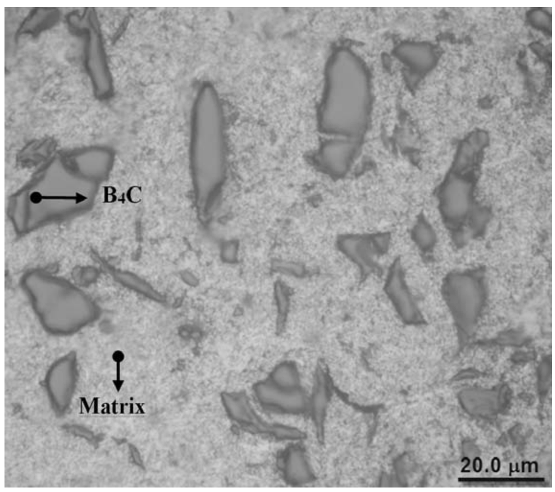


Figure 5: Microstructure of the composite having the mass fraction 15 % B_4C
Slika 5: Mikrostruktura kompozita z masnim deležem 15 % B_4C

tensile strength values were obtained when the B_4C particle fraction was 15 %. Generally, an increase in the particle fraction increases the strength of the composite material but, at the same time, reduces ductility due to an increased dislocation density.[19] In this study, it was observed that the ceramic reinforcements added to the aluminum matrix reduced the ductility of the composite material and made it more brittle (**Table 2**). The fact that the strength of the composite having 25 % particle fraction was lower than the strength of the composites having mass fractions 10 % B_4C and 15 % B_4C can be attributed to the increase in the interfacial decompositions between the particles and the matrix.[20]

Table 2: Strength results of the B_4C-reinforced MMC
Tabela 2: Trdnost MMC, ojačanega z B_4C

B_4C particle mass fraction *w*/%	Yield strength MPa	Tensile strength MPa	Elongation %
10	491	527	22.2
15	532	599	6.9
25	328	408	4.8

3.2 Cutting Forces and Torques

According to the experimental results, the effects of the cutting parameters such as particle fraction, cutting speed, feed rate and cutting-tool material on the thrust force and torque were given in **Figures 4** and **5**. The cutting forces increased with the particle weight fraction, and the rate of this increment for HSS tools was higher than that for the carbide tools with greater particle fractions. An increase in the weight fraction of the B_4C particles within the aluminum matrix increased the hardness of the composite causing a rapid tool wear due to a more intense contact with the cutting edge. Therefore, increasing both the weight fraction and the area of hard particles being in contact with the cutting tool resulted in an increase in the friction and flow strength of the cutting tool-chip as well as the cutting tool-workpiece interface. On the other hand, it could be observed from **Figures 6** and **7** that the thrust force and cutting torque increased with the feed rate, but they decreased with the cutting speed. Previous researchers stated that the most important factor affecting the cutting forces was the feed rate[3,8–12,16] and this was confirmed by our study. Since the chip volume removed per revolution of the cutting tool increased with an increase in the feed rate, the thrust force and cutting torque increased as well.[21]

When experimental results were analyzed in terms of the cutting-tool material, higher thrust forces, ranging from 150 N to 250 N, were produced with HSS tools than with carbide tools while drilling the 25 % B_4C reinforced MMCs. This situation could be attributed to the hardness of the cutting tool and to the wear mecha-

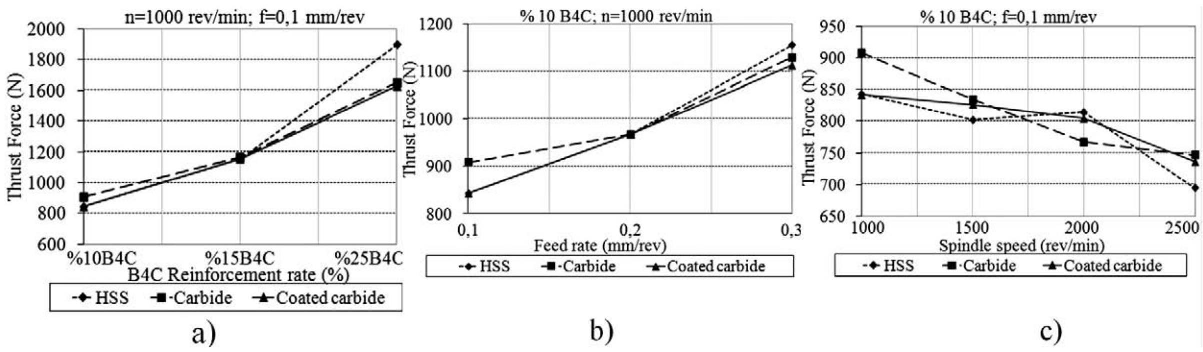


Figure 6: Effect of machining parameters on the thrust force: a) particle mass fraction, *w*/%, b) feed rate, mm/r, c) spindle speed, r/min
Slika 6: Vpliv parametrov obdelave na potisno silo: a) vsebnost delcev v masnih deležih, *w*/%, b) hitrost podajanja, mm/r, c) hitrost vrtenja vretena, r/min

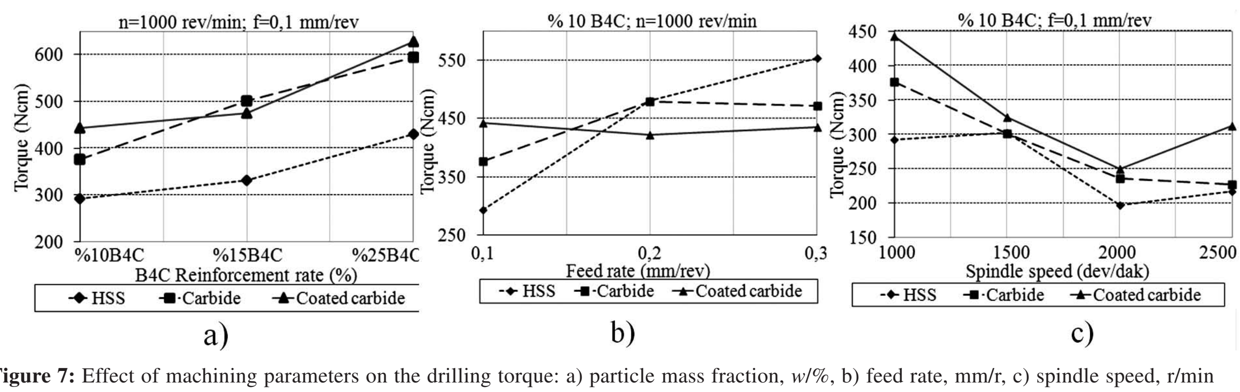


Figure 7: Effect of machining parameters on the drilling torque: a) particle mass fraction, *w*/%, b) feed rate, mm/r, c) spindle speed, r/min
Slika 7: Vpliv parametrov obdelave na navor pri vrtanju: a) vsebnost delcev v masnih deležih, *w*/%, b) hitrost podajanja, mm/r, c) hitrost vrtenja vretena, r/min

nisms of the drilling tool. Since HSS tools had a lower hardness than carbide tools, higher thrust forces were produced with HSS drills, especially with a higher particle fraction due to the tool flank wear. When the particle fraction was less than 25 %, the difference between the thrust forces produced by HSS and carbide tools was relatively lower (20 N–40 N). However, the test results indicated that HSS drills generally produced less cutting torques than carbide drills as shown in **Figure 7**. This condition might be attributed to the point angle of the drill because the thrust force and cutting torque increased with an increased point angle.[22] Therefore, it was concluded that HSS drills produced less cutting torques than carbide drills due to having a point angle smaller by 5° than carbide drills. Consequentially, although lower cutting forces were produced by PCD diamond tools according to the existing literature[3], carbide tools could be preferred for machining MMCs taking into account the production-cost balance.

3.3 Optimization with the Taguchi Method

In this section, optimization of drilling parameters was carried out in terms of drilling forces with the Taguchi analysis. The importance order of the effects of each control factor on drilling forces was identified. For this purpose, the factors selected in the Taguchi experimental design and the levels of these factors are shown in **Table 3**. A four-factor, 27-line and three-level L_{27} (3^{13}) orthogonal array was chosen since it has the ability to control the interactions among the factors.[23–25]

In the Taguchi method, there are three categories such as "the smallest is better", "he biggest is better" and "the nominal is better" for the calculation of the signal/noise (S/N) ratio. In this study, since "the lowest" thrust-force and cutting-torque values were desired for the optimization, "the smallest is better" calculation method was chosen. In the i_{th} experiment, the S/N ratio η_i can be calculated using the following equation[14,26,27]:

$$\eta_i = -10 \log_{10} \left(\frac{1}{n} \sum_{i=1}^{n} Y_i^2 \right) \tag{1}$$

where n is the number of replications and Y_i is the measured characteristic value (i.e, the thrust force or cutting torque). The calculated S/N ratios (η) of the thrust forces and cutting torques are given in **Table 4**.

Table 3: Factors and levels used in the experiments
Tabela 3: Faktorji in stopnje, uporabljene pri eksperimentu

Process parameters	Units	Levels		
		Level 1	Level 2	Level 3
Particle fraction (A)	%	10	15	25
Feed rate (B)	mm/r	0.1	0.2	0.3
Spindle speed (C)	r/min	1000	1500	2000
Drill material (D)		HSS	Carbide	TiAlN-coated carbide

Table 4: Experimental design with the L_{27} orthogonal array and the S/N ratios
Tabela 4: Oblikovanje preizkusov z ortogonalno razporeditvijo L_{27} in razmerje S/N

Test No	A	B	C	D	Thrust force (N)	S/N ratio for thrust force	Torque (N cm)	S/N ratio for torque
1	1	1	1	1	843.2	–58.52	293	–49.34
2	1	1	2	2	834.3	–58.43	300.9	–49.57
3	1	1	3	3	804.3	–58.11	249.3	–47.93
4	1	2	1	2	966.8	–59.71	478.4	–53.60
5	1	2	2	3	924.1	–59.31	344	–50.73
6	1	2	3	1	880.7	–58.90	294	–49.37
7	1	3	1	3	1113.3	–60.93	434.7	–52.76
8	1	3	2	1	1048	–60.41	446.6	–53.00
9	1	3	3	2	1096	–60.80	291.3	–49.29
10	2	1	1	2	1168	–61.35	500.3	–53.99
11	2	1	2	3	1062	–60.53	398.5	–52.01
12	2	1	3	1	973.3	–59.77	309.1	–49.80
13	2	2	1	3	1244	–61.90	496.7	–53.92
14	2	2	2	1	1132	–61.07	370.6	–51.38
15	2	2	3	2	1089	–60.74	340	–50.63
16	2	3	1	1	1313	–62.37	578.3	–55.24
17	2	3	2	2	1310	–62.35	328	–50.32
18	2	3	3	3	1218	–61.71	388.5	–51.79
19	3	1	1	3	1631	–64.25	627.1	–55.95
20	3	1	2	1	1655	–64.37	434.1	–52.75
21	3	1	3	2	1374	–62.76	415.4	–52.37
22	3	2	1	1	1826	–65.23	496.2	–53.91
23	3	2	2	2	1477	–63.39	492.8	–53.85
24	3	2	3	3	1379	–62.79	547.8	–54.77
25	3	3	1	2	1835	–65.27	674.1	–56.57
26	3	3	2	3	1629	–64.24	641	–56.14
27	3	3	3	1	1441	–63.17	492.2	–53.84

The arithmetic average of S/N ratios for the levels of each control factor was calculated with respect to the thrust force and the cutting torque (**Table 5**). In addition, after arranging the difference between the maximum and minimum S/N ratios for each factor in a descending order, the degree of influence of each factor on the thrust force or cutting torque was found. Accordingly, the effective control factors for the thrust force were particle fraction, feed rate, spindle speed and drill-bit material (**Table 5**). The optimum machining parameters for the thrust force and drilling torque are found at the level where each factor has the largest S/N ratio.[14] Therefore, the optimal machining conditions for the thrust force were found to be the particle fraction of 10 %, feed rate of 0.1 mm/r, spindle speed of 2000 r/min and drill material of TiAlN-coated carbide. Similarly, the optimal machining conditions for the drilling torque were found to be the particle fraction of 10 %, feed rate of 0.1 mm/r, spindle speed of 2000 r/min and a HSS drill.

The effect graph of each control factor for the thrust force and drilling torque, according to the mean responses, was given in **Figures 8a** and **8b**, respectively. Both **Figures 8a** and **8b** showed that the thrust force and drilling torque increased with an increase in the particle fraction and the feed rate, while the thrust force and cutting torque decreased with an increase in the spindle speed. However, the effect of the drill-bit material on the thrust force was very low.

Table 5: Average S/N ratios for each factor and level with regard to thrust force and cutting torque
Tabela 5: Povprečje razmerja S/N za vsak faktor in stopnjo glede na potisno silo in navor pri rezanju

	Level	A	B	C	D
For thrust force	1	–59.4564*	–60.8976*	–62.1689	–61.5337
	2	–61.3091	–61.4479	–61.5665	–61.6429
	3	–63.941	–62.361	–60.9711*	–61.53*
	Difference	4.4846	1.4634	1.1978	0.1092
	rank	1	2	3	4
For torque					
	1	–50.6201*	–51.5226*	–53.9199	–52.0704*
	2	–52.1194	–52.4621	–52.194	–52.2421
	3	–54.462	–53.2168	–51.0877*	–52.8891
	Difference	3.8419	1.6942	2.8322	0.8187
	rank	1	3	2	4

* = Optimal level

3.4 Analysis of Variance (ANOVA)

The purpose of the analysis of variance was to determine which parameter significantly affects the cutting forces.[28] ANOVA was performed to find whether individual factors and their interactions that affect the cutting forces were meaningful. According to the ANOVA results presented in **Table 6**, the most influential factor for the thrust force was found to be the particle fraction of 80.23 %. The other important factors were feed rate (6.72 %) and spindle speed (6.73 %). Similarly, the most influential factor for the drilling torque was found to be the particle fraction of 45.99 %, followed by spindle speed (25.25 %) and feed rate (8.75 %) as seen in **Table 7**. In addition, the effect of the drill-bit material on the cutting forces was found to be small. F_{test} values for the cutting forces, with regard to the factor interactions, were not meaningful since they were smaller than F_{table} values.[27] Hence, the statistical significance of interactions was minimum and it could be neglected.

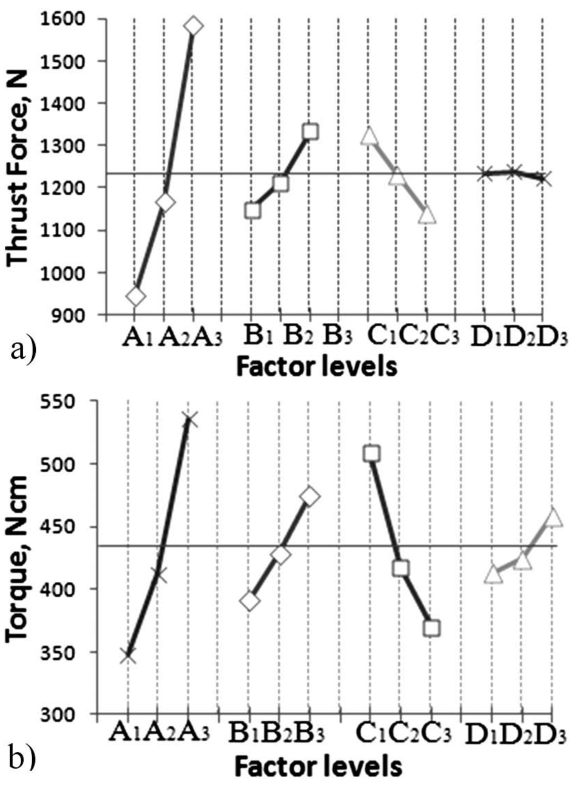


Figure 8: Mean effect graphs of responses: a) thrust force, b) drilling torque
Slika 8: Graf učinka povprečnih rezultatov: a) potisna sila, b) navor pri vrtanju

Table 6: ANOVA results for the thrust force
Tabela 6: Rezultati ANOVA za potisno silo

Factor	DF	SS	V	F_{test}	PD
Particle fraction (A)	2	1882587	941294	210.5	80.23
Feed rate (B)	2	157716	78858	17.63	6.721
Spindle speed (C)	2	157829	78915	17.65	6.726
Drill material (D)	2	1250	624.9	0.1397	0.053 3
AxB	4	25505	6376	1.426	1.087
AxC	4	79868	19967	4.465	3.404
BxC	4	15006	3751	0.8388	0.639 5
Error	6	26835	4472		1.144
Total	26	2346595			100

DF: Degree of Freedom, *SS*: Sum of Squares, *V*: Variance, *PD*: Percentage Distribution. $F_{table(0.05;2;6)} = 5.14$, $F_{table(0.05;4;6)} = 4.53$

Table 7: ANOVA results for the drilling torque
Tabela 7: Rezultati ANOVA za navor pri vrtanju

Factor	DF	SS	V	F_{test}	PD
Particle fraction (A)	2	163615	81808	15.92	45.99
Feed rate (B)	2	31123	15562	3.029	8.749
Spindle speed (C)	2	89834	44917	8.742	25.25
Drill material (D)	2	10230	5115	0.995	2.876
AxB	4	11959	2990	0.582	3.362
AxC	4	12466	3116	0.607	3.504
BxC	4	5689	1422	0.277	1.599
Error	6	30829	5138		8.666
Total	26	355745			100

DF: Degree of Freedom, *SS*: Sum of Squares, *V*: Variance, *PD*: Percentage Distribution. $F_{table(0.05;2;6)} = 5.14$, $F_{table(0.05;4;6)} = 4.53$

3.5 Confirmation Experiments

The final step of the Taguchi experimental design process includes confirmation experiments.[14,27] For this aim, the results of the experiments were compared with the predicted values with the Taguchi method and the error rates were obtained. S/N ratios $\eta_{predict}$ were predicted using the following model:[14,26]

$$\eta_{predict} = \eta_m + \sum_{i=1}^{k} (\eta_i - \eta_m) \tag{2}$$

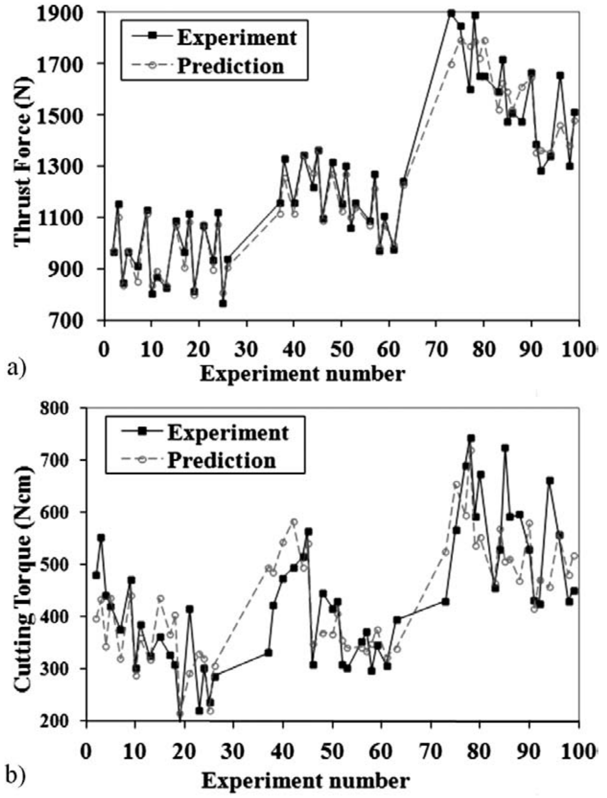


Figure 9: Comparison of the predicted and experimental results: a) thrust force (R^2 = 0.946), b) drilling torque (R^2 = 0.644)

Slika 9: Primerjava napovedanih in eksperimentalno določenih rezultatov: a) potisna sila (R^2 = 0,946), b) navor pri vrtanju (R^2 = 0,644)

where η_m is the total mean of the S/N ratios, η_i is the mean S/N ratio at the optimum level and k is the number of the main design parameters that significantly affect the performance characteristics.

After predicting the S/N ratios other than 27 experiments (with Eq.2), the thrust forces and drilling torques were calculated using the following equation:[26]

$$Y_{\text{predict}} = 10^{\left(\frac{-S/N}{20}\right)} \tag{3}$$

where Y_{predict} is the thrust force or drilling torque with regard to the S/N ratio. **Figure 9** represents the comparison between the predicted and experimental results according to the experiment numbers. These results show that the Taguchi method can be applied successfully in predicting the thrust forces with the coefficient of determination R^2 = 0.946 (**Figure 7a**). The value of R^2 for the prediction of the cutting torques was 0.644, but the R^2 value for 54 of 100 experiments was 0.85.

4 CONCLUSIONS

In this study, aluminum MMCs containing three different weight fractions of B_4C particles were produced with the PM technique, and drilling experiments were carried out to study the effects of the machining parameters on the thrust force and cutting torque. Moreover, the optimum drilling parameters were obtained for the performance characteristics (thrust force and torque) using the Taguchi analysis. The obtained results can be summarized as follows:

- An increase in the proportion of the B_4C particle caused a decreased ductility of the material but an increased hardness of the composite. The highest tensile strength was obtained with the 15 % B_4C particle fraction.
- According to the experimental results, the cutting forces significantly increased with an increase in the B_4C fraction and the feed rate but decreased with an increase in the spindle speed.
- HSS tools produced more thrust forces than the two carbide tools especially when drilling the composites with higher particle fractions. On the other hand, the coated and the solid carbide tools produced similar thrust forces. However, the coated tools produced somewhat higher drilling torques than the uncoated ones.
- With the Taguchi and ANOVA analysis, the effective factors for the thrust force and drilling torque were found to be the particle-weight fraction and feed rate, respectively. Furthermore, the effects of the cutting tool material and the interactions of the factors on the thrust force and cutting torque were found to be very low.

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