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ORIGINAL ARTICLE

Statistical analysis of process parameters in drilling of AL/SIC$_P$ metal matrix composite

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Abstract This paper presents a statistical analysis of process parameters for surface roughness in drilling of Al/SiCp metal matrix composite. The experimental studies were conducted under varying spindle speed, feed rate, drill type, point angle of drill, and heat treatment. The settings of drilling parameters were determined by using Taguchi experimental design method. The level of importance of the drilling parameters is determined by using analysis of variance. The optimum drilling parameter combination was obtained by using the analysis of signal-to-noise ratio. Through statistical analysis of response variables and signal-to-noise ratios, the determined significant factors were the feed rate and tool type. Confirmation tests verified that the selected optimal combination of process parameter through Taguchi design was able to achieve desired surface roughness. The optimal drilling performance for the surface roughness was obtained at 0.16 mm/rev feed rate, 260 rev/min spindle speed, 130° drill point angle, carbide drill type, and as-received heat treatment settings.

Keywords Metal matrix composite · Drilling · Surface roughness · Taguchi method · ANOVA

1 Introduction

Metal matrix composites (MMC) have been successfully applied in aerospace industries since 1970s; and in the middle of 1980s, these materials reached the automobile, aerospace, and other industries and nowadays its use is gaining importance [1, 2]. With the advent of new processing techniques, the technological interest and research activity in the development of metal matrix composites have increased rapidly in recent years [1]. These materials are based on a metal matrix, usually aluminum, magnesium or titanium matrix, reinforced with a disperse phase, particles, fibers or whiskers, of silicon carbide, aluminum oxide, etc [3]. In comparison with unreinforced monolithic alloys and resin matrix composites, MMCs offer higher stiffness and strength values, lower coefficient of thermal expansion and the ability to be used at higher temperatures. Despite the superior mechanical and thermal properties of particulate metal matrix composites, their poor machinability is the main deterrent to their substitution of metal parts. However, there are a lot of disadvantages such us lower fatigue behavior or increased brittleness due to the presence of hard reinforcement and defects at the interface. The hard SiC particles acts as abrasive between cutting tool and work piece and resulting in formation of high tool wear, poor surface finish, high drilling forces, and burr formation [4]. Particulate metal matrix composites (PMMC) are economically cheaper in both raw materials and fabrication processes, and have potential for applications requiring relatively large volume production [5]. PMMCs offer superior wear resistance while many engineering components made from PMMCs are produced by the near net-shape forming and casting processes, they frequently require machining to achieve the desired dimensions and surface finish [6].

In drilling operations, surface roughness determines the economics of machining and rate of production. In setting the machining parameters, the main goal is the minimum surface roughness. The setting of machining parameters relies strongly on the experience of operators and machining parameter tables provided by machine tool builders.

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Operators in machine shops usually use "trial and error" approaches to determine the proper drilling cutting parameters in order to achieve a desired surface roughness. Obviously, the "trial and error" method is not effective and efficient, and the achievement of a desirable value is a repetitive and empirical process that can be very time consuming [7]. It is difficult to utilize the optimal functions of a machine owing to there being too many adjustable machining parameters. The optimum use of the capability of the drilling process requires the selection of an appropriate set of machining parameters. In this study, the optimum parameters in drilling process were obtained using a statistical method. Turning, boring, and milling operations of aluminum alloys are carried out in the literature at much higher speed with longer tool life and improved surface finish. One of the main goals of this present study is to determine the optimal cutting conditions for manufacturers having machine tools with low speeds as well. To the best of the knowledge of the authors of this work, there is no published work studying the effect of process parameters on surface roughness statistically in drilling of a %17 Al/SiC_p metal matrix composites. The variation of surface roughness with process parameters and optimization of process settings for minimum surface roughness should be investigated in drilling. In this study, the effects of the process parameters and their level of significance on the surface roughness are statistically evaluated by analysis of variance (ANOVA).

2 Literature review

Some of the published studies on drilling of metal matrix composite materials are presented below:

Mubaraki et al. [4] examined the wear behavior of high speed steel (HSS), WC, and polycrystalline diamond (PCD) tools in drilling of Al_2O_3 reinforced Al alloy particulate metal matrix composites, and tried to establish a correlation between the flank wear and measurement of forces. El-Gallab and Sklad [5] studied tool performance and work piece integrity of machining of Al/SiC PMMCs. Surface roughness measurement show that the surface roughness improves with an increase in the feed rate and cutting speed, but slightly deteriorates with an increase in the depth of cut. This was attributed to the reduction in the flank wear of the tool with an increase in the feed rate. Zhang and Cheng [7] studied to efficiently determine the optimal drilling parameters to achieve the smallest surface roughness value for 1018 low carbon steel plates under varying conditions and they optimized the surface quality in a CNC drilling operation by Taguchi design. Brown and Surappa [8] studied the machinability of Al–Si–graphitic particle composite and they are under the opinion that the reduction in machining forces with graphite reinforcement content is due mostly to a decrease in the shear flow stress rather than to lower chip-rake-face friction. The results indicate that machined surfaces of Al–Si alloy–graphite composites tend to be rougher than similar surfaces on similar material without graphite because of deeper holes or valleys. Konig and Grass [9] studied the surface texture of holes and analyzed the drilling of fiber reinforced thermosets (carbon fiber, glass fiber, aramid fiber) by quantifying the amount of machining damage using ten-point height and width of the damage zone. Darwish et al. [10] investigated the effect of the cutting parameters and tool wear to the work piece surface roughness produced, which could be misleading. This is because in most cases during the machining of Al/SiC_p MMCs the surface roughness produced, the surface roughness is much lower than that obtained during the machining of the matrix alloy alone. Monaghan and O'Reily [11] attributed the improved surface finish to the burnishing or honing effect produced by the action of small SiC particles trapped between the flank face of tool and the work piece surface. Monaghan and O'Reily [12] used coated and uncoated high speed steel, carbide and PCD-tipped drills and solid carbide drills in the drilling tests. The results indicate that the hardness of the tool material has a significant influence on cutting edge wear and on the drilling torque, surface finish, and thrust forces. Wern et al. [13] was shown that the width of the damage in a composite material is a function of the drill geometry and the feed rate. Oden and Ericsson [14] studied the near-surface deformation in an alumina–silicon carbide whisker composite due to grinding. Songmene and Balazinzki [15] worked on drilling and milling of Al/SiCp, Al/SiCp–Gr and Al/Al2O3–Gr composite and they are under the opinion that the incorporation of graphite particle into aluminum MMCs and the variation of hard particle content improve the machinability of the composite. Barnes et al. [16] showed that softer as-extruded and solution-treated materials produced less wear and lower cutting forces than the harder-aged materials. However, the height of the burrs produced during drilling was found to be greater than the softer materials and the quality of the drilled surface was also inferior. Davim and Antonio [17] conducted drilling tests with the intention of developing optimal drilling conditions using genetic algorithm approach. They noticed a predominantly abrasive wear mechanism attributed to the hard particles in the matrix. The surface finish was found to be affected by the feed rate and not by the cutting speed. Ramulu et al. [18] reported that the alumina particulates caused extremely rapid flank wear in drilling tools, when machining Al_2O_3 particulate reinforced aluminum-based MMC. Among the three tool materials studied, PCD drills possessed the highest resistance to tool wear and they are recommended for finish machining operations under most

Table 1 The chemical composition of test materials

Material	Chemical composition (wt.%)					
	Cu	Mg	Mn	Fe	Si	Al
Composite matrix	3.69	1.42	0.55	0.01	0.01	Balance

cutting conditions. The carbide tipped drill also showed acceptable drilling forces and hole quality. In this case, carbide tipped drills can be used under compromised conditions. HSS drills are unsuitable for drilling of ceramic reinforced MMCs because of very high tool wear, poor hole quality, and higher drilling forces induced. The ANOVA, response surface methodology was used to analyze experimental data and developed regression models. They concluded that drilling forces and average surface roughness values are greatly influenced by the feed rate than the cutting speed. Davim [19] studied the drilling of metal matrix composites based on Taguchi technique to find the influence of cutting parameters on tool wear, torque, and surface finish and the interactions between the above factors. He analyzed the data by analysis of variance and found the percentage of influence of each factor on responses. In addition, he presented a study of the influence of cutting parameters and cutting time on drilling MMCs based on the techniques of Taguchi. Tosun and Muratoglu [20], dealt with the surface integrity of drilled Al/SiCp MMCs. Dry drilling tests at different drilling conditions have been conducted in order to investigate the effect of the various cutting parameters on the surface quality and the extent of the deformation of drilled surface due to drilling. Tosun and Ozler [21] investigated the possibility of application of statistical approaches to see the level of importance of machining parameters on surface roughness and tool life in hot turning operations. Sahin [22] presented a study of the weight loss model of aluminum alloy composites with 10 wt.% SiC particles by molten metal mixing method based on the techniques of Taguchi. He predicted the optimal combination of the testing parameters. It was shown that the predicted weight loss of the composite samples was found to lie close to that of the experimentally observed ones. Tosun [23] used Grey relational analysis for optimizing the drilling process parameters such as feed rate, cutting speed, drill type, and point angles of drill for the work piece surface roughness and burr height. Jadoun et al. [24] discussed the influence of cutting parameters on drilling characteristics of a hybrid metal matrix composites. The composites are fabricated using stir casting method. The Taguchi design of experiments and ANOVA are employed to analyze the drilling characteristics of these composites. Their study applied cutting velocity and feed rate as experiment factors and used feed force, surface finish, and burr height as evaluation criteria. The study found that the evaluation criteria were greatly impacted by feed rather than by speed.

3 Experimental procedure

The material used for drilling test samples is 2124 Aluminum–SiC_p composite containing 17 vol.% SiC particulate reinforced material provided by Aerospace Metal Composites Limited (UK). It is produced by powder metallurgy techniques and the average size of the SiC particulates was 3 μm. The powder was mechanically cold

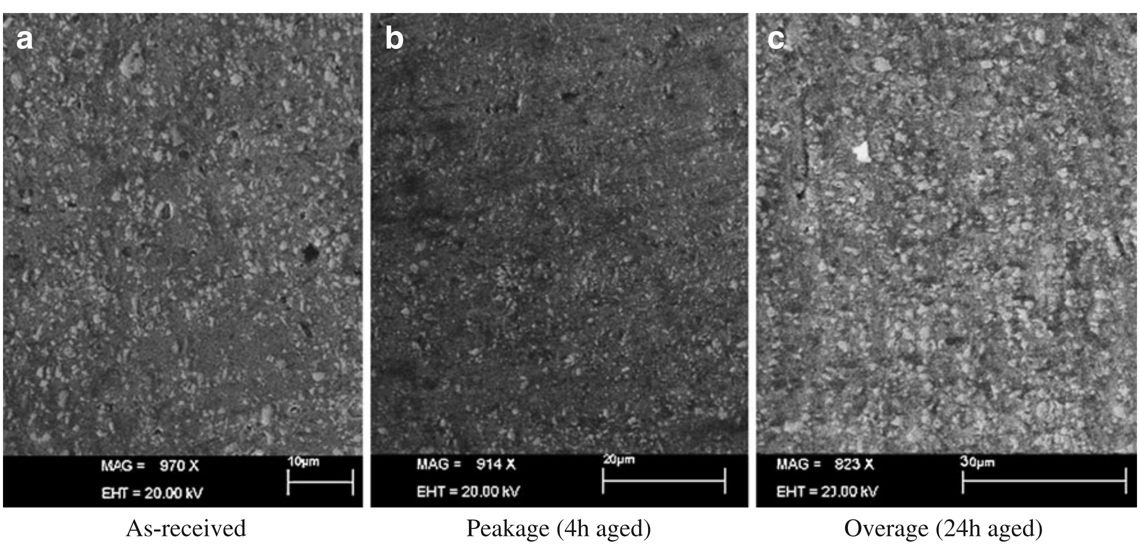

Fig. 1 SEM photographs of the microstructure of the composite material at the different heat treatment conditions: **a** as-received, **b** peak age (4 h aged), **c** overage (24 h aged)

Fig. 2 Photograph of experimental setup

mixed with SiC particulate and was subsequently isostatically hot compacted at 500°C, followed by forging at 475°C and hot rolled at 475°C. The chemical composition and the microstructure of the test material are given in Table 1 and Fig. 1.

All drilling tests were performed on a Lagun Ft-2 (Spain) vertical machining center (Fig. 2). Samples were prepared in the form of 10×10×15 mm by cutting in Sodick A320D a wire electrical discharge machine. Experiments were conducted under different machining parameters, namely, drill point angle, drill type, cutting speed, spindle speed, and heat treatment. The settings of machining parameters were determined by using Taguchi experimental design method.

In order to observe the effect of matrix hardness on the drilling performance of the composite materials, three heat treatment conditions were investigated: as-received, solution treated at 500°C 4 h and aged at 190°C for 4 h (to the peak-age condition), and solution treated at 500°C 4 h and

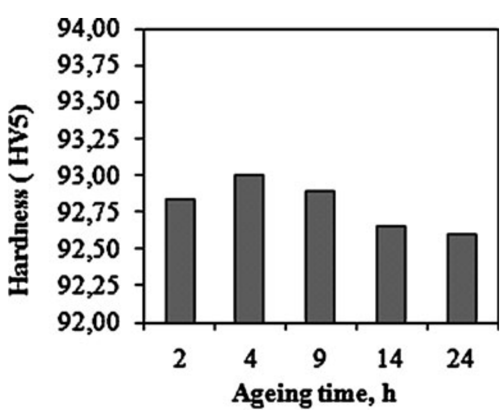

Fig. 3 The variation of the hardness value as a function of aging time for composite material

Table 2 The experimental parameters and their values

Parameters	Values
Drill type	HSS, TiN, carbide
Drill point angle (°)	90, 118, 130
Heat treatment	As-received, peak age, overage
Feed rate (mm/rev)	0.08, 0.16
Spindle speed (rpm)	260, 1330

aged at 190°C for 24 h (to the overage condition). All aged and solutionized samples were kept in a refrigerator right after the heat treatments. In order to determine the optimum time of the peak and overaging, five different times were selected for aging time after solution treatment at the same aging temperature. According to the macrohardness measurement taken on that aged samples (Fig. 3), 4 and 24 h were accepted as peak-aging and overaging time, respectively.

Drills used in the experiments have *N* type, diameter of 5 mm, and a helix angle of 30°± 3. For each experiment, a new twist drill was used. The drill materials tested included: HSS, titanium–nitride-coated HSS, solid carbide drills, all provided by Si-Metal Limited (Turkey).

The coolant liquid was not used in all drilling test. The experiments were performed under different speeds of 260 and 1,330 rpm and feed rates of 0.08 and 0.16 mm/rev. All experimental conditions were summarized and are given in Table 2.

The surface finish of each drilled hole was measured with the aid of a Mitutoyo Surfest SJ-201 (Japan) type instrument using a cut-off length of 0.8 mm and sampling number of five. Surface roughness readings were taken at four positions spaced at 90° intervals around the hole circumference and approximately midway down the depth

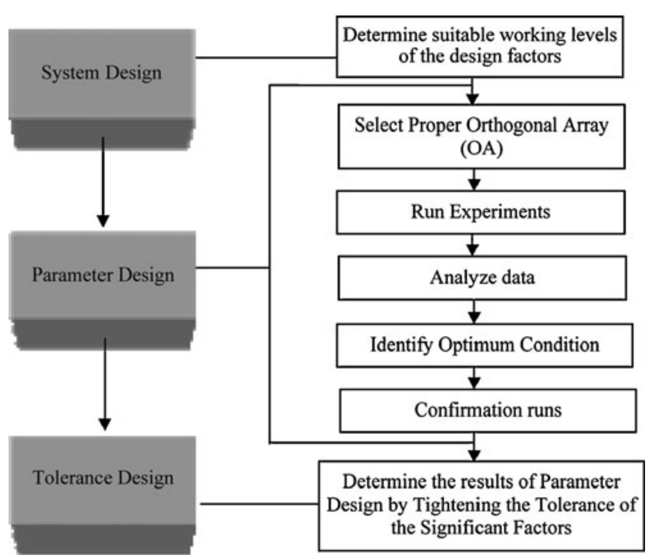

Fig. 4 Taguchi design procedure [7]

Table 3 Process parameter settings used in the experiments

Symbol	Process parameter	Level 1	Level 2	Level 3
A	Feed rate (mm/rev)	0.08	0.16	–
B	Spindle speed (rpm)	260	1330	–
C	Drill point angle (°)	90	118	130
D	Drill type	HSS	TiN	Carbide
E	Heat treatment	As-received	Peak age	Overage

Table 4 Experimental design using L_{36} orthogonal array

Exp. no	Feed rate (mm/rev) A	Spindle speed (rev/min) B	Drill point angle C	Drill type D	Heat treatment E	Ra (μm)
1	1	1	1	1	1	0.92
2	1	1	1	2	2	0.27
3	1	1	1	3	3	0.37
4	1	2	1	1	1	1.70
5	1	2	1	2	2	0.36
6	1	2	1	3	3	0.47
7	2	1	1	1	1	0.98
8	2	1	1	2	2	0.17
9	2	1	1	3	3	0.39
10	2	2	1	1	1	1.05
11	2	2	1	2	2	0.20
12	2	2	1	3	3	0.51
13	1	1	2	1	2	1.53
14	1	1	2	2	3	0.36
15	1	1	2	3	1	0.37
16	1	2	2	1	2	2.64
17	1	2	2	2	3	0.20
18	1	2	2	3	1	0.28
19	2	1	2	1	2	1.07
20	2	1	2	2	3	0.23
21	2	1	2	3	1	0.26
22	2	2	2	1	2	0.80
23	2	2	2	2	3	0.18
24	2	2	2	3	1	0.24
25	1	1	3	1	3	0.87
26	1	1	3	2	1	0.36
27	1	1	3	3	2	0.34
28	1	2	3	1	3	1.62
29	1	2	3	2	1	0.29
30	1	2	3	3	2	0.37
31	2	1	3	1	3	0.94
32	2	1	3	2	1	0.23
33	2	1	3	3	2	0.33
34	2	2	3	1	3	1.85
35	2	2	3	2	1	0.21
36	2	2	3	3	2	0.18

Table 5 S/N ratio values of surface roughness

Process parameter	Mean S/N ratio (dB)		
	Level 1	Level 2	Level 3
A	5.01	6.95[a]	–
B	6.30[a]	5.66	–
C	5.61	5.32	7.01[a]
D	−1.82	8.44	11.32[a]
E	7.41[a]	5.94	4.59

Total mean value, 5.98

[a] Optimal level

of the hole. The surface roughness of each hole was taken as the average of the four readings.

4 Design of experiment based on Taguchi method

The Taguchi design is a design of experiment (DOE) approach developed by Dr. Genichi Taguchi in order to improve the quality of manufactured goods in Japan. Although similar to factorial design of experiment, the Taguchi design only conducts balanced (orthogonal) experimental combinations, which makes the Taguchi design even more efficient than a fractional factorial design (surface roughness optimization of drilling). In this study, Taguchi method, a powerful tool for parameter design of performance characteristics, was used to determine optimal machining parameters for minimum surface roughness in drilling of Al/SiCp metal–matrix composites [7]. The complete procedure of the Taguchi design method can be divided into three stages: system design, parameter design, and tolerance design as shown in Fig. 4 [7]. The steps involved in parameter design of Taguchi's method are as follows [24]:

1. Identify the response functions and the process parameters to be evaluated.

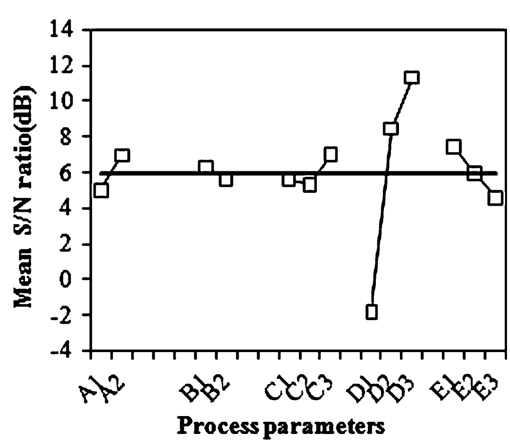

Fig. 5 The influence of process parameters on the surface roughness

Table 6 Result of ANOVA for the surface roughness

Process parameter	Degree of freedom	Sum of square	Variance	F_{A0}	Contribution %
Feed rate	2	34.11	17.05	3.11	2.44
Spindle speed	2	3.61	1.80	0.33	0.26
Drill point angle	3	19.55	6.51	1.19	1.40
Drill type	3	1146.35	382.11	69.83	81.92
Heat treatment	3	47.81	15.93	2.91	3.42
Error	27	147.73	5.47	–	10.56
Total	35	1399.18	–	–	100

2. Determine the number of levels for the process parameters and possible interaction between them.
3. Select the appropriate orthogonal array, assign the process parameters to the orthogonal array, and conduct the experiments accordingly.
4. Analyze the experimental results and select the optimum level of process parameters.
5. Verify the optimal process parameters through a confirmation experiment.

Taguchi proposed to acquire the characteristic data by using orthogonal arrays and to analyze the performance measure from the data to decide the optimal process parameters. In Taguchi method, process parameters which influence the products are separated into two main groups: control factors and noise factors. The control factors are used to select the best conditions for stability in design of manufacturing process, whereas the noise factors denote all factors that cause variation. Like in the reviewed literature, this study included spindle speed and feed rate as control factors. Tooling information such as tool wear, tool type, tool point angle, and tool material is also important; therefore, three types of drills with the same geometric specification (one made of high speed steel, TiN-coated HSS, and the other solid carbide) were employed in the experiment. In this way, the tool type and tool point angle was treated as a control factor to study its impact on the drilled holes surface quality [7]. This method uses a special design of orthogonal arrays to study the entire parameter space with small number of experiments only [23]. In this study, four machining parameters were used as control factors and each parameter was designed to have three levels or two levels, denoted 1, 2, and 3 (Table 3). According to the Taguchi quality design concept, an *L*36 orthogonal arrays table with 36 rows (corresponding to the number of experiments) was chosen for the experiments (Table 4). When the experimental parameters and their levels used in this study was taken into consideration, *L36* orthogonal array is the most appropriate choice.

5 Analysis and discussion of experimental results

The analysis of variance was used to establish statistically significant machining parameters and the percent contribution of these parameters on the surface roughness. In Taguchi method [23], a loss function is used to calculate the deviation between the experimental value and the desired value. This loss function is further transformed into a signal-to-noise (S/N) ratio. There are several S/N ratios available depending on type of characteristics; lower is better (LB), nominal is best, or higher is better. In drilling, the lower surface roughness is the indication of better performance. Therefore, the "LB" for the surface roughness was selected for obtaining optimum machining performance characteristic. For LB, the definition of the loss function (*L*) for machining performance results yi of *n* repeated number is:

$$L_{ij} = \frac{1}{n}\sum_{i=1}^{n} y_i^2 \quad (1)$$

The S/N ratio for the *i*th performance characteristic in the *j*th experiment can be expressed as:

$$\text{S/N ratio} = -10\log\left(L_{ij}\right) \quad (2)$$

Regardless of category of the performance characteristics, a greater S/N ratio value corresponds to a better performance.

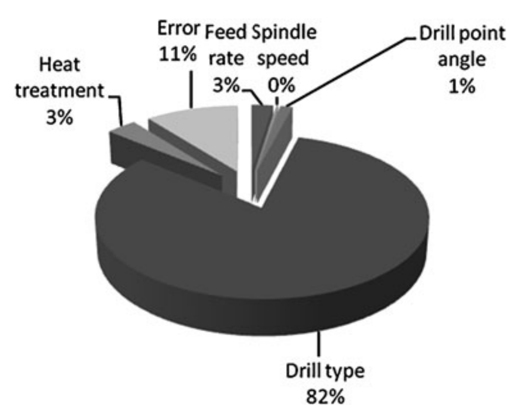

Fig. 6 Factors and their contributions (%) on the surface roughness with respect to ANOVA

Table 7 Results of the confirmation experiment for Ra

Level	Starting drilling parameters	Optimal drilling parameters	
		Prediction	Experiment
	A2B2C2D2E2	A2B1C3D3E1	A2B1C3D3E1
Surface roughness (Ra)(μm)	0.36	0.19	0.23
S/N ratio for Ra (dB)	8.87	14.36	12.76

Improvement S/N ratio for Ra=3.89 dB

Therefore, the optimal level of the machining parameters is the level with the greatest S/N ratio value. By applying the Eqs. 1 and 2, the S/N ratio values for each experiment of L_{36} (Table 4) were calculated (Table 5).

Based on the analysis of S/N ratio, the optimal machining performance for the surface roughness was obtained at 0.16 mm/rev feed rate (level 2), 260 rev/min spindle speed (level 1), 130° drill point angle (level 3), carbide drill type (level 3) and as-received heat treatment (level 1) settings. Figure 5 shows the effect of process parameters on the surface roughness.

These results are coherent with the experimental results. The relative importance among the cutting parameters for the surface roughness still needs to be investigated by using the ANOVA method so that optimal combinations of the cutting parameter levels can be determined more accurately [18].

The results of ANOVA for the surface roughness are shown in Table 6. The relative importance of the machining parameters with respect to the surface roughness was investigated to determine more accurately the optimum combinations of the machining parameters by using ANOVA. Statistically, F test provides a decision at some confidence level as to whether these estimates are significantly different. Larger F value indicates that the variation of the process parameter makes a big change on the performance characteristics. F values of the machining parameters are compared with the appropriate confidence table. When the F value of the machining parameter is bigger than $F\alpha,v1,v2$ value of the confidence table, where α is risk, $v1$ and $v2$ are degrees of freedom associated with numerator and denominator [23]. The results of ANOVA for the surface roughness are shown in Table 6.

In Fig. 6, the most effect on the surface roughness of the work piece is appeared drill type and feed rate, respectively. The experimental error is 11% for the surface roughness. The percent contribution due to error provides an estimate of adequacy of the experiment. The percent contribution due to error is low (%15 or less); therefore, it is assumed that the conditions were precisely controlled. Spindle speed, heat treatment, and drill point angle were relatively insignificant. Percent contribution indicates the relative power of a factor to reduce variation. For a factor with a high percent contribution, a small variation will have a great influence on the performance.

6 Confirmation experiments

The confirmation experiment is the final step in the first iteration of the DOE process. The confirmation is performed by conducting a test using a combination of the factors and levels previously evaluated. In this study, after determining the optimum conditions and predicting the response under these conditions, a new experiment was designed and conducted with the optimum levels of the cutting parameters. The final step is to predict and verify the improvement of the performance characteristic. The predicted multi S/N ratio $\widehat{\eta}$ using the optimal levels of $\widetilde{\eta}$ the cutting parameters can be calculated as:

$$\widehat{\eta} = \eta_m + (\sum_{i=1}^{p} (\overline{\eta}_i - \eta_m)) \quad (3)$$

where η_m is total mean of S/N ratio, η_i is the mean of S/N ratio at the optimal level, and p is the number of the main machining parameters that significantly affect the performance. The results of experimental confirmation using optimal machining parameters are shown in Table 7.

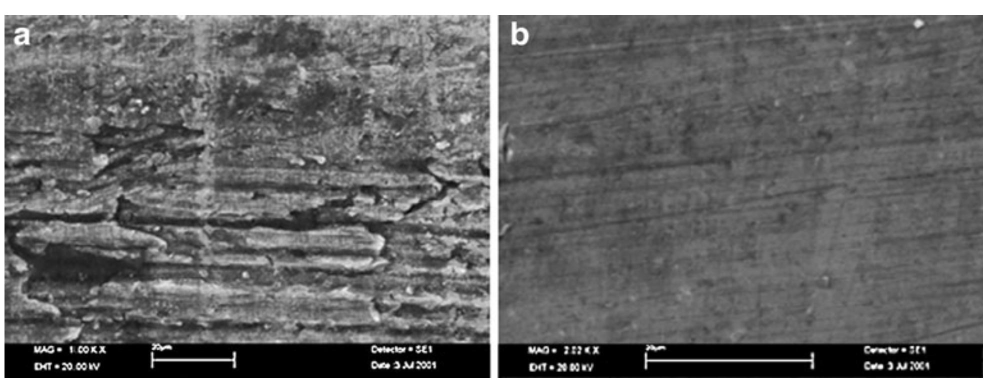

Fig. 7 SEM photographs of the drilled surface under conditions of 90° point angle, 260 rpm spindle speed, 0.08 mm/rev feed rate and as-received **a** HSS drill and **b** carbide drill

The improvement in S/N ratio from the starting drilling parameters to the level of optimal drilling parameters is 3.89 dB. The Ra is decreased by 1.56 times. So, the Ra is greatly improved by using the approach. Table 7 shows the comparison of the predicted Ra with the actual Ra using the optimal drilling parameters. The experimental results confirmed the validity of the used Taguchi method for enhancing the machining performance and optimizing the machining parameters. The Ra is greatly improved by using the approach. Also, the microstructures photographs of specimens obtained min and max surface roughness are confirmed results of confirmation (Fig. 7).

7 Conclusions

The results from this study performed on a statistical analysis of process parameters in drilling of Al/SiCp metal matrix composite can be summarized as follows:

1. Based on the analysis of variance and *F* test analysis, the most effective parameters on the work piece surface roughness have appeared drill type and feed rate, respectively. Spindle speed, drill point angle, and heat treatment have been determined being insignificant factors on the surface roughness.
2. An optimum parameter combination for the minimum surface roughness was obtained by using the analysis of S/N ratio. Based on the analysis of S/N ratio, the optimal machining performance for the surface roughness was obtained at 0.16 mm/rev feed rate (level 2), 260 rev/min spindle speed (level 1), 130° drill point angle (level 3), carbide drill type (level 3), and as-received heat treatment (level 1) settings.
3. The results showed that drill type was about 15 times more important than the second ranking factor (feed rate) for controlling the surface roughness. The effects introduced by tool type and feed rate on surface quality in this study were larger than the effect of spindle speed, heat treatment, and drill point angle.
4. The confirmation tests indicated that it is possible to decrease surface roughness significantly by using the proposed statistical technique. The experimental results confirmed the validity of the used Taguchi method for enhancing the machining performance and optimizing the machining parameters in drilling operations.
5. This entire study was accomplished with a number of experimental runs, given the number of control and noise factors, suggesting that Taguchi parameter design is an efficient and effective method for optimizing surface roughness performance.

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